Contract Report GL-98-1
January 1998

US Army Corps of Engineers
Waterways Experiment Station

Seismic Hazards of the Upper Mississippi Embayment

by Roy Van Arsdale, University of Memphis

WES

Prepared for Headquarters, U.S. Army Corps of Engineers

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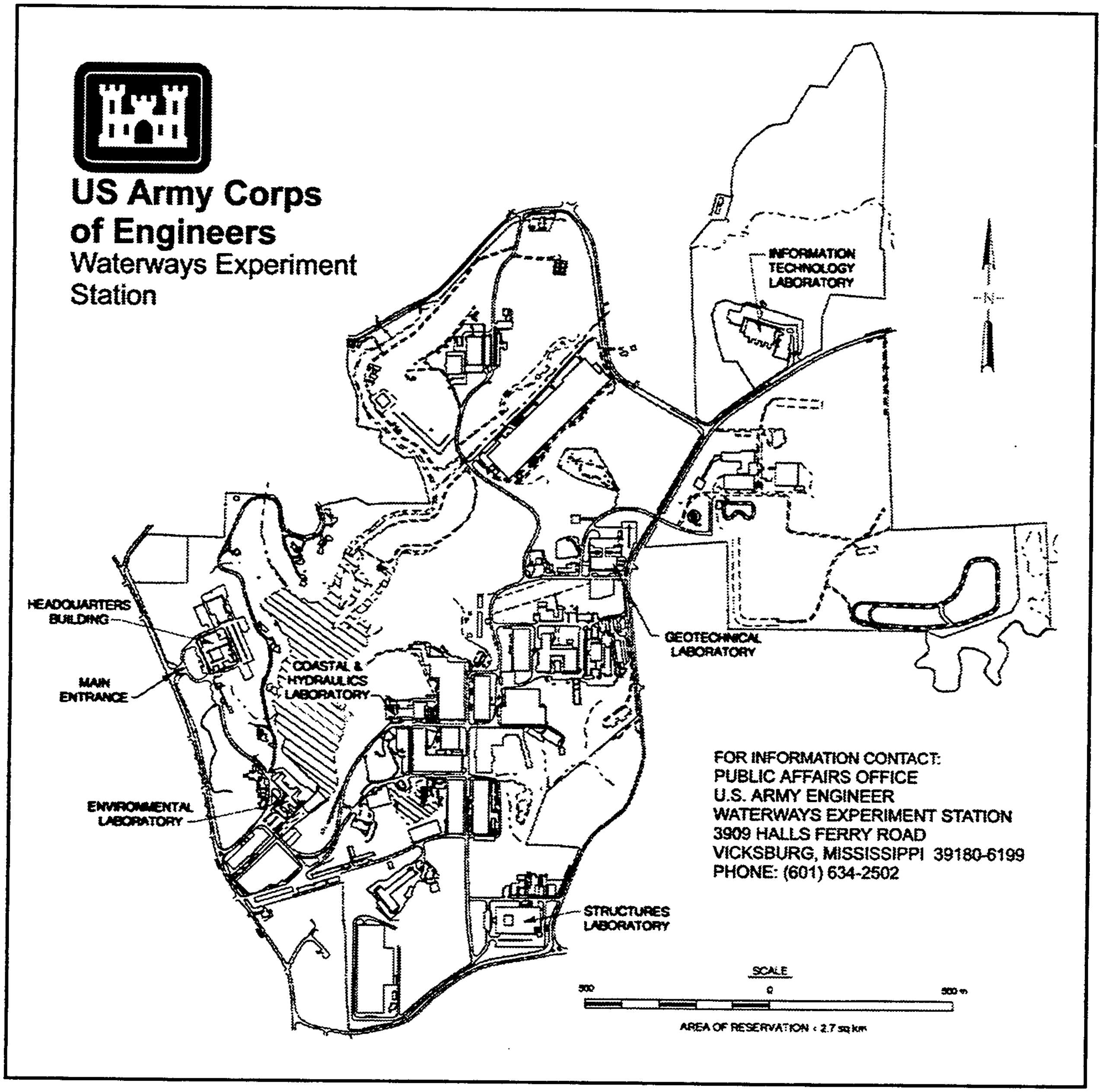
Final report

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Monitored by U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, MS 39180-6199



Waterways Experiment Station Cataloging-in-Publication Data

Van Arsdale, Roy Burbank, 1950-
Seismic hazards of the upper Mississippi embayment / by Roy Van Arsdale ; prepared for the U.S. Army Corps of Engineers ; monitored by the U.S. Army Engineer Waterways Experiment Station.
132 p. : ill. ; 28 cm. — (Contract report ; GL-98-1)
Includes bibliographical references.
1. Paleoseismicity. 2. Earthquakes — Mississippi River Valley. 3. Faults (Geology) —Mississippi River Valley. I. United States. Army. Corps of Engineers. II. U.S. Army Engineer Waterways Experiment Station. III. Geotechnical Laboratory (U.S. Army Engineer Waterways Experiment Station) IV. Title. V. Series: Contract report (U.S. Army Engineer Waterways Experiment Station) ; GL-98-1.
TA7 W34c no.GL-98-1

Contents

Preface

This report was sponsored by the Department of the Army and is part of the ongoing Civil Works studies in Earthquake Engineering: Geological-Seismological Evaluation of Earthquake Hazards.

The report was prepared by Dr. Roy Van Arsdale, University of Memphis, under contract No. DACW 39-97-M-0277.

At the time of publication of this report, Dr. W. F. Marcuson, III, was Director of the Geotechnical Laboratory. Director of WES was Dr. Robert W. Whalin. Commander was COL Robin R. Cababa, EN.

Seismic Hazards of the Upper Mississippi Embayment

Report to the United States Army Corps of Engineers

Abstract

Earthquakes are a major hazard in the middle Mississippi River valley of the upper Mississippi embayment. Microseismicity along the New Madrid seismic zone is illuminating faults that are believed responsible for the great New Madrid earthquakes of 1811-1812. These faults are right-lateral strike-slip faults within the Blytheville arch and western margin of the Reelfoot rift that are linked by the southwest-dipping Reelfoot reverse fault. The Bootheel lineament and back thrusts of the Reelfoot fault may also have slipped in 1811-12. Geomorphic effects of the 1811-12 sequence include displacement of the Mississippi River; uplift of the Lake County uplift, Tiptonville dome, Blytheville arch; subsidence of Reelfoot Lake, Big Lake, and Lake St. Francis; landslides on the eastern bluffs of the Mississippi River valley; and extensive liquefaction. In addition there is evidence for 1811-12 landsliding on the eastern margin of Crowley's Ridge, formation of a lake on the Obion River, and formation of seismic craters on the loess-covered eastern Mississippi Valley bluffs.

Peripheral to the New Madrid seismic zone; the Big Creek, Commerce, and Crittenden County faults have Holocene displacement and faults along the margins of Crowley's Ridge have Pleistocene displacement. The margins of Sikeston Ridge are underlain by faults that apparently lifted the ridge in Quaternary time. Similarly, the eastern Mississippi Valley bluffs are underlain by faults that appear to have affected the current position of the Mississippi River. Thus, there is evidence for widespread Quaternary faulting within the upper Mississippi

embayment.

Paleoliquefaction and trench excavations across the Reelfoot fault reveal a minimum of 3 prehistoric earthquakes and an estimated recurrence interval of 450 years. This very high strain rate may be transitory and/or deformation may move around the upper Mississippi embayment through time. Since the Plio-Pleistocene Lafayette Formation and subsequent Quaternary section is incised into the Eocene section, it appears that the northern Mississippi embayment has been rising during Quaternary time. Thus, the widespread faulting may be a consequence of Quaternary uplift of the northern Mississippi embayment.

Future earthquakes would cause widespread and potentially catastrophic effects on the built environment of the Mississippi River. Of particular concern is the Reelfoot reverse fault that trends from near Dyersburg, Tennessee, to New Madrid, Missouri. Displacement, like that which occurred on February 7, 1812 on the Reelfoot fault and its associated back thrusts, would displace the Mississippi River bed at a miniumum of 5 locations resulting in breaking of river levees, warping the river profile, and forming temporary ponding and rapids/waterfalls. Liquefaction was dramatic in 1811-12 and is also a major concern in future earthquakes. Although the water table is generally lower today in the Mississippi River valley due to drainage ditches, it remains high below the river levees. The levees may be vulnerable to liquefaction effects.

Introduction

The purpose of this report is to assess the seismic hazards of the upper Mississippi embayment and in particular the New Madrid seismic zone (NMSZ) (Fig. 1). The NMSZ is a zone of

microseismic activity that lies within the middle Mississippi River Valley, in the northwestern portion of the Mississippi embayment (Figs. 1 and 2). It is within this zone of current seismicity, that the great New Madrid earthquakes of 1811-1812 are believed to have occurred (Fig. 2) (Johnston, 1996; Johnston and Schweig, 1996).

Geologic History of the Mississippi Embayment

The NMSZ lies within the northwestern portion of the Mississippi embayment, a broad and gentle south-southwest-plunging syncline of Cretaceous and Tertiary age (Stearns, 1957; Stearns and Marcher, 1962) (Fig. 1). In order to more fully understand the geologic structure of the NMSZ, it is necessary to review the structural history of the Mississippi embayment.

Drill hole data and exposures in the Ozarks of southeastern Missouri indicate that, during late Precambrian time, the upper Mississippi embayment area was a subaerial landscape with between 150 and 450 m of topographic relief (Schwalb, 1982; Buschbach and Schwalb, 1984) cut into Middle Proterozoic granites and rhyolites (Bickford, 1988) (Fig. 3). This landscape was dramatically altered by the initiation of the northeast-trending Mississippi Valley graben in Late Precambrian or Early Cambrian time during extension of the North American continent (Thomas, 1989, 1991; Johnson et al., 1994; Marshak and Paulsen, 1996) (Figs. 4 and 5). The Mississippi Valley graben is equivalent to the Reelfoot rift and Reelfoot graben and will hereafter be referred to as the Reelfoot rift because this is the term most commonly used within the seismologic literature (Ervin and McGinnis, 1975; Kane et al., 1981; Hildenbrand et al., 1982; Thomas, 1991; Johnson et al., 1994; Langenheim and Hildenbrand, 1997). Reelfoot rift is approximately 300 km long, 70 km wide, and has up to 8 km of structural relief (Nelson and Zhang, 1991). The rift boundaries are defined primarily by the magnetic signature of

apparent rift-margin intrusives. Contouring of the top of the Precambrian section indicates that there may be late Precambrian and Cambrian basins within the Reelfoot rift (Fig. 6) (Dart and Swolfs, in press). Furthermore, these basins may be bound by northwest-trending faults that have been mapped in the adjacent Ozark plateau (Fig. 7) (Cox, 1988b; Clendenin et al., 1989).

Middle Ordovician through Early Devonian unconformities mark marine transgressions and regressions that may have been accompanied by reactivation of rift-bounding faults (Howe, 1985). Late Devonian deformation resulted in Upper Devonian black shales lying with angular unconformity over strata as old as Ordovician. Upper Paleozoic through middle Cretaceous strata are absent within most of the upper Mississippi embayment. Thus, the Mississippi embayment is characterized by having a major unconformity with Late Cretaceous strata overlying lower Paleozoic strata.

Formation of the Mississippi embayment initiated in Late Cretaceous time with subsidence and deposition of Upper Cretaceous terrestrial and marine sediments (Stearns, 1957; Pryor, 1960). Marine deposition continued through mid-Eocene time. The axis of the embayment is nearly coincident with the underlying Reelfoot rift. Braile et al. (1982), among others, have proposed that the Mississippi embayment formed as a consequence of reactivation of the ancient Reelfoot rift during opening of the Gulf of Mexico. However, Cox and Van Arsdale (1997) point out that Late Cretaceous subsidence of the Mississippi embayment is much younger than Jurassic opening of the Gulf of Mexico and that geologic data indicate an arch existed along the axis of the Mississippi embayment during mid-Cretaceous time (Fig. 8). An arch preserved beneath the Cretaceous section is particularly well illustrated in cross section E-E' of Thomas (1991) (Figs. 9 and 10). The Paleozoic subcrop map reveals that uplift of the Mississippi

Valley arch during middle Cretaceous time resulted in erosion to as deep as the Cambrian section over the Pascola arch (Fig. 11). Subsequent subsidence of the arch in Late Cretaceous time started the formation of the Mississippi embayment. Mid-Cretaceous uplift and subsequent Late Cretaceous/Tertiary subsidence of the Mississippi embayment is believed to be due to passing of a hotspot beneath the mid-continent (Cox and Van Arsdale, 1997) (Figs. 12 and 13). In support of this interpretation is the observation that most of the plutons of the upper Mississippi embayment are of mid-Cretaceous age and are truncated by the overlying Late Cretaceous unconformity (Cox and Van Arsdale, 1997).

In the interpretation by Cox and Van Arsdale (1997), an arch existed along the axis of the Mississippi Valley during mid-Cretaceous time, thus the Mississippi River came into existence during Late Cretaceous time with subsidence of the arch/embayment. This interpretation is supported by the stratigraphic record in the Gulf of Mexico. The northern margin of the Gulf of Mexico was a major reef system through the Jurassic and did not experience major clastic deposition from the Mississippi River basin until Late Cretaceous time.

Late Eocene compression resulted in minor faulting and folding within the embayment (Howe and Thompson, 1984; Luzietti et al., 1992). Absence of Oligocene and Miocene strata suggests that, during this time, the embayment area was subaerially exposed. In Pliocene time, the embayment was subjected to Mississippi Valley incision and deposition of the Pliocene-Pleistocene Upland Gravels (Lafayette Fm) preserved on Crowley's Ridge and the embayment perimeter (Potter, 1955; Autin et al., 1991; Self, 1993). The Upland Gravels is a fluvial sequence that unconformably overlies the Eocene section. Coincident with valley incision was deposition of at least 4 loess blankets on Crowley's Ridge and on the eastern bluffs of the Mississipppi River valley (Autin et al., 1991). The Quaternary has also been a time of

Mississippi River incision. Evidence for Quaternary incision includes river entrenchment below the Upland Gravel, glacial outwash inset into Eocene strata, and extensive Pleistocene terraces. The modern geomorphology of the Mississippi Valley began in the Holocene with the transition of the Mississippi River from a braided glacial outwash river to a meandering river (Autin et al., 1991; Saucier, 1994). The Mississippi River apparently is continuing to incise its valley since Holocene sediments are topographically lower than the river's Pleistocene deposits.

This structural history of the Mississippi embayment is reflected in its stratigraphy. Late Cretaceous and Tertiary subsidence of the embayment has resulted in an Upper Cretaceous and Tertiary section that thickens to the southwest (Fig. 14). Mid-Cretaceous uplift of the Mississippi Valley arch controls the preservation of Paleozoic stratigraphy beneath the Cretaceous unconformity (Fig. 11). The oldest Paleozoic section forms the erosion surface in the crestal portion of the arch and progressively younger Paleozoic strata are preserved to the east and west on the arch's flanks. Thus, it is difficult to present a characteristic stratigraphic section for the Mississippi embayment; the preserved Paleozoic section depends on where one is in the embayment. Approximately 575 oil exploration wells have been drilled in the upper Mississippi embayment north of the Ouachita Front (Fig. 1) (Dart, 1992). Of the wells near the NMSZ, detailed descriptions are available for the Fort Pillow Test Well (Moore and Brown, 1969), New Madrid Test Well X-1 (Crone, 1981) (Fig. 15), and Dow No. 1 Wilson well (Nelson and Zhang, 1991) (Fig. 2). In general, the pre-Cretaceous fill of the Reelfoot rift basin consists of a lower syn-rift Lamotte Formation and an overlying post-rift sequence consisting of the Bonneterre and Elvins Formations and the Knox Group.

Structure of the Mississippi Embayment

As discussed above, the Mississippi embayment is a south-southwest plunging syncline. North of the Ouachita Front, the syncline plunges 0.21^{o} southwest and is slightly asymmetric with western limb dips of 0.59^{o} and eastern limb dips of 0.34^{o}. Thus, although the Mississippi embayment is commonly portrayed in figures as a conic trough, the top of the Paleozoic-base of the Cretaceous is essentially a flat surface.

Seismogenic and potentially seismogenic basement faults are believed to have originated in Late Precambrian and Early Cambrian time during formation of the Reelfoot Rift. The rift is largely defined by geophysical maps (Ervin and McGinness, 1975; Hildenbrand, 1985; Langenheim and Hildenbrand, 1997) (Figs. 16 and 17). A number of excellent 1:250,000 scale maps of the NMSZ have been compiled that illustrate various types of geological and geophysical data (Rhea and Wheeler, 1994; 1995; Wheeler and Rhea, 1994; Wheeler et al., 1994; Dart, 1995). Clear definition of faults is achieved through seismic reflection, of which there is very little in the upper Mississippi embayment (see Dart, 1995, for the status of reflection lines in the northern Mississippi embayment). Nelson and Zhang (1991) collected COCORP lines across the embayment that imaged the geologic section to depths of 20 seconds of two-way-travel-time. The Reelfoot rift basin and underlying structure is evident in these COCORP lines (Fig. 18 and Figure 3 of Nelson and Zhang). Based on the characteristics of deep crustal reflections, these authors speculate that Reelfoot rift may have opened along the older Precambrian Grenville Front (Fig. 19).

The COCORP lines reveal that Reelfoot rift contains steeply-dipping faults and is bounded by inward-dipping listric normal faults. Most of the faults imaged in the COCORP data do not

appear to have post-Cretaceous displacement. However, this is probably a function of the resolution of the data; COCORP is designed for deep crustal imaging. Oil exploration seismic reflection lines (Howe, 1985; Crone et al., 1985), vibroseis lines (Zoback, 1979; Hamilton and Zoback, 1982), a Mississippi River reflection survey (Shedlock and Harding, 1982), Mini-Sosie lines (Sexton and Jones, 1986; 1988; Luzietti et al., 1992; Schweig et al., 1992; Stephenson et al., 1995; Van Arsdale et al., 1995a; Purser, 1996), and S-wave studies (Woolery et al., 1996) reveal post-Cretaceous faulting on numerous faults in the upper Mississippi embayment. Dow Chemical Corporation acquired 6,400 km of seismic reflection lines across portions of the upper Mississippi embayment (Howe and Thompson, 1984; Howe, 1985; Crone et al., 1985). These intermediate-depth (5 s of TWTT = 10-12 km) reflection lines reveal Cenozoic faulting. Mini-Sosie lines image the uppermost crust between depths of 1,200 m and 70 m, and therefore have been obtained to determine shallow deformation. Mini-Sosie surveys have revealed Tertiary and Quaternary faulting beneath the margins of Crowley's Ridge (Van Arsdale et al., 1994; 1995a), Sikestons Ridge (Sexton, 1992), Blytheville arch (Van Arsdale et al., 1996), Benton Hills (Palmer et al., 1997), along the Reelfoot fault (Sexton and Jones, 1986; 1988; Purser, 1996), Cottonwood Grove and Ridgely faults (Stephenson et al., 1995; Purser, 1996), Bootheel lineament (Schweig et al., 1992; Sexton et al., 1992), Crittenden County fault (Luzietti et al., 1992; 1995), and one of the west-bounding faults of the Reelfoot rift (Van Arsdale et al., 1995a) (Fig. 20).

Western Margin of the Reelfoot Rift

Various studies demonstrate that faults within the western margin of the Reelfoot rift have Quaternary displacement and thus may be seismic source zones (Schweig and Van Arsdale, 1996) (Fig. 20). Geophysical studies along the Commerce geophysical lineament suggest that

this is an active rift-margin fault (Fig. 16) (Langenheim and Hildenbrand, 1997). A segment of the fault, at Thebes Gap, has Quaternary displacement that appears to displace Peoria loess (Figs. 20 and 21) (Harrison and Schultz, 1994; Harrison, personal communication). A second fault within the western margin of the Reelfoot rift just northeast of Jonesboro, Arkansas, appears to have Quaternary reactivation (Fig. 22). Although not well tied to a particular structure, the northern arm of the NMSZ appears to follow the western margin of the Reelfoot rift (Fig. 2). This northern arm of seismicity may be occurring along the same fault identified northeast of Jonesboro (Van Arsdale et al., 1995a). Strain measurements indicate that the western half of the Reelfoot rift is undergoing right-lateral shear at a rate of 0.1 microstrain per year; 1/3 that of the San Andreas fault (Fig. 23) (Liu et al., 1992). Thus, the current stress field appears to be loading strain energy within the western margin of the Reelfoot rift.

Crowley's Ridge

Crowley's Ridge is a topographic ridge that trends diagonally across the underlying western Reelfoot rift boundary (Figs. 20 and 24). However, Mini-Sosie profiles have revealed faulting beneath the ridge margins (Figs. 24 and 25) (Van Arsdale et al., 1995a) and geomorphic analyses of the ridge suggest that it may be a horst, which is subdivided into different segments underlain by discrete fault blocks (Cox, 1988a; Boyd and Schumm, 1995; Spitz and Schumm, 1997). Most of the uplift is Tertiary in age but there is geomorphic evidence that arching occurred in Wisconsin time (Van Arsdale et al., 1995a). A trench excavated across the western margin of the ridge, revealed a flexed soil E-horizon; however, no conclusive evidence of surface faulting was found (Figs. 24 and 26) (Drouin, 1995).

Eastern Margin of the Reelfoot Rift

The eastern margin of the Reelfoot rift has been tectonically active in Quaternary time along the Crittenden County fault zone, 25 km northwest of Memphis (Figs. 20, 27 - 31) (Crone, 1992; Luzietti et al., 1992; 1995; Williams et al., 1995). Figures 30 and 31 reveal that Mississippi River flood plain sediments are faulted to within 7 m of the ground surface. Since the flood plain is Holocene in age at this location, then the faulting reflects Holocene movement. However, a trench excavated over the Crittenden County fault found no clear evidence of surface faulting (Crone et al., 1995). As more microseisms are plotted, there also appears to be an alignment of seismicity along the eastern margin north of Memphis (Fig. 32) (Chiu et al., in press).

New Madrid Seismic Zone

The principal seismic activity within the upper Mississippi embayment is interior to the Reelfoot rift along the NMSZ (Fig. 2). The NMSZ consists of 3 principal trends of seismicity; two northeast-trending arms with a connecting northwest-trending arm. This seismicity pattern has been interpreted as a northeast-trending right-lateral strike-slip fault system with a compressional left-stepover zone (Fig. 33) (Russ, 1982; Schweig and Ellis, 1994; Van Arsdale, 1997). The southern arm is coincident with the subcrop Blytheville arch (also called Charlie's Ridge), the central arm is coincident with the subcrop Pascola arch and surface Lake County uplift, and the northern arm is coincident with the western margin of the Reelfoot rift.

The southern seismicity arm extends from Marked Tree, Arkansas, to Reelfoot Lake, Tennessee, and it is believed that the December 16, 1811, M 8.1 New Madrid earthquake occurred on this

segment (Fig. 2) (Johnston, 1996; Johnston and Schweig, 1996). Earthquakes, whose focal mechanisms primarily reflect right-lateral strike-slip motion, are occurring at depths between 4 and 12 km in Precambrian granites and Lower Paleozoic sedimentary rocks of the Blytheville arch (Crone et al., 1985) (Figs. 34 and 35). [This earthquake focal range is true for all of the NMSZ.] The Blytheville arch is thus a major structure that is localizing seismicity. The arch has 1 km of structural relief on the Paleozoic section and formed before Late Cretaceous time (probably Mid-Cretaceous) because the Upper Cretaceous section has only minor structural displacement. There remains quite a bit of disagreement about the structural origin of the arch. Crone et al. (1985) interpreted the arch to be the consequence of laccolithic intrusion along the arch's axis, whereas McKeown et al. (1990) have proposed that the arch is due to diapiric intrusion. An early model by Howe (1985), later supported by Nelson and Zhang (1991), interprets the axial uplift as resulting from Late Paleozoic compressional reactivation of a syn-rift fault. I prefer the mechanism of the last model, but would modify it slightly. Figure 36 suggests that the arch can be explained by tectonic inversion of the graben bounded by the faults labeled F1 and F2. Specifically, I believe that a Reelfoot sub-graben subsided during Paleozoic deposition and then was subsequently compressed, thereby lifting and arching a locally thicker Paleozoic section. A very similar structural setting has been interpreted for the Arkansas earthquake swarm (Fig. 37) (Schweig et al., 1991).

Vibroseis (Hamilton and Zoback, 1982) and Mini-Sosie (Van Arsdale et al., 1996) reflection data reveal faulted Tertiary and Quaternary strata along the Blytheville arch. Hamilton and Zoback (1982) cite 80 m of down-to-the-southeast cumulative displacement of Cretaceous and Tertiary reflectors across the arch's southeastern boundary near Osceola, Arkansas. Shedlock and Harding (1982) document faults with vertical displacements of 33 to 50 feet associated with a broad arch with 180 feet of structural relief on the Cretaceous section near

Caruthersville, Arkansas. Near Big Lake, Arkansas (Fig. 38), Van Arsdale et al. (1996) also document Quaternary faulting. This suggests that the Blytheville arch has been lifted over much of its length during Quaternary time and perhaps during the December 16, 1811, New Madrid earthquake.

The Reelfoot fault of northwestern Tennessee is believed to be responsible for the February 7, 1812, **M** 8.0 New Madrid earthquake (Johnston, 1996; Johnston and Schweig, 1996) (Figs. 38 and 39). This fault is an up-to-the-southwest thrust/reverse fault within the stepover zone of the NMSZ. The Reelfoot fault surfaces as the Reelfoot scarp, which has been mapped from the southwestern margin of Reelfoot Lake into the town of New Madrid, Missouri, for a total distance of 32 km (Fig. 39) (Van Arsdale et al., 1995b; Kelson et al., 1996). Unpublished Mini-Sosie lines along the Obion River of western Tennessee, reveal a fault that is tentatively identified as the Reelfoot fault. Thus, the Reelfoot fault appears to continue 20 km southeast of Reelfoot Lake and, based on the current microseismicity pattern, the fault probably continues another 20 km to near Dyersburg, Tennessee (Fig. 2) for a total length of 72 km.

The north-trending Reelfoot scarp forms the eastern margin of the Lake County uplift in Tennessee and turns northwest in Kentucky to New Madrid, Missouri, paralleling the seismicity trend (Figs. 39 and 2). A recent Mini-Sosie line acquired along the southern margin of Reelfoot Lake and extending into the Mississippi Valley bluffs reveals that episodic movement on the Reelfoot thrust, apparently since the Cretaceous, has resulted in 70 m of displacement at the top of the Paleozoic and 10 m at the ground surface (Fig. 40) (Purser, 1996). Identical episodic movement appears to have occurred on the northeast-striking Ridgely fault, thereby suggesting that the multilple main shocks of 1811-1812 were not unique in the history of the NMSZ. This same reflection line reveals that the Mississippi Valley bluffs are underlain by the Ridgely fault

zone, which has down-to-the-west displacement. Thus, the bluffs appear to be structurally controlled east of Reelfoot Lake (Purser, 1996; Van Arsdale et al., 1996).

The Lake county uplift is a consequence of deformation within the hanging wall of the Reelfoot fault (Axford, 1996; Purser, 1996). Essentially, the tiptonville dome is a horst atop the Lake County uplift horst, within the hanging wall of the Reelfoot fault (Fig. 41). If the Figure 41 model is correct, then the Lake County uplift and Tiptonville dome are bounded on their west sides by kink bands (back thrusts) that probably had displacement during the February 7 earthquake.

The northern arm of the NMSZ extends from New Madrid towards Charleston, Missouri. It appears that, like the southern arm, this segment is coincident with a northeast-striking fault zone and that right-lateral faulting is the most common type of fault plane solution. However, as revealed in Figure 2, this arm is not parallel to the rift margin. The structure of this northern seismicity trend has not been well imaged with seismic reflection and therefore we know very little about it (Hamilton and Zoback, 1982).

Seismicity near New Madrid, Missouri, is complicated by a minor westerly trend. McKeown (1982) proposed that the Bloomfield pluton (Figs. 2 and 42) is locally influencing the seismicity and that the seismicity essentially wraps around the pluton. McKeown (1982) also notes that plutons in the Mississippi embayment, like the Bloomfield pluton, consist of different rheologies and may thus be acting as stress concentrators. Although the Bloomfield pluton may be locally influencing the distribution of earthquakes there is no convincing evidence of plutons along most of the NMSZ (Nelson and Zhang, 1991).

The Bootheel lineament is believed to be a coseismic fault of the New Madrid 1811-1812 earthquake sequence (Schweig and Marple, 1991; Marple and Schweig, 1992; Johnston and Schweig, 1996). However, there is no evidence of surface faulting along the lineament. It should be pointed out; however, that there is also no evidence of 1811-1812 surface faulting along the Blytheville arch or the northern NMSZ seismicity arm. Mini-Sosie reflection data does reveal flower structures beneath the Bootheel lineament (Schweig et al., 1992; Sexton et al., 1992) and the lineament has been interpreted as a linking fault that is in the process of bypassing the unstable Reelfoot fault (Fig. 39 inset and Fig. 68) (Schweig and Ellis, 1994).

Sikeston Ridge

Sikeston Ridge is a 50 km long by 12 to 5 km wide topographic ridge that trends northerly from New Madrid, Missouri (Fig. 43). This ridge has been explained to have originated as a Pleistocene erosional remnant left between two Pleistocene courses of the Mississippi River (Saucier, 1974; 1994). However, numerous faults underly the ridge (Fig. 44) (Sexton, 1992). The faults with the most displacement are inward-dipping normal faults that are near the ridge's margins. Essentially, Sikeston Ridge overlies a graben. If Sikeston Ridge is tectonic in origin, then the graben has been tectonically inverted. That is, normal faults within the margins of the graben have been reactivated as reverse faults. This reactivation must have occurred in Pleistocene time because the ridge is capped by Pleistocene sediments (Saucier, 1974).

Discussion of the Structure of the Upper Mississippi Embayment

Faults with Quaternary displacement appear to be along northeast-trending Reelfoot rift faults

and the complex stepover zone within the central portion of the rift (Fig. 20). Right-lateral strike-slip motion on the rift-parallel faults is compatible with the contemporary stress field. Seismicity defining the northwest-trending Reelfoot thrust fault appears to extend from the eastern margin of the Reelfoot rift to beyond the currently mapped western rift margin. It is therefore possible that the Reelfoot fault is truncated at its western end by an unidentified rift-margin fault or by the Commerce geophysical lineament. The fault-bend fold model suggests that deformation within the stepover zone is controlled by the Reelfoot fault and associated parallel kink bands (back thrusts) in the hanging wall (Figs. 20 and 41).

Crowley's Ridge has Tertiary faulting beneath its margins but it appears that the most recent movement on these faults may be Pleistocene (Van Arsdale et al., 1995a). However, it must be noted that the northern portion of Crowley's Ridge, and presumably its bounding faults, are nearly parallel to the rift-margin faults and is parallel to the Bootheel lineament. Therefore, I propose that the faults that bound the northern portion of Crowley's Ridge are capable of generating earthquakes.

Much work remains to resolve the structure of the upper Mississippi embayment. I believe that the most direct way to decipher the area's structure is to collect more seismic reflection data. Although most of the faults illustrated in Figure 20 may be capable of generating damaging earthquakes in the Mississippi Valley, understanding the Reelfoot fault and its hanging wall deformation is of particular importance to the integrity of the Mississippi River. If the faults, as presented in Figures 20 and 41, are correct, then the Reelfoot fault crosses the Mississippi River at 3 locations, and the back thrusts cross the Mississippi River at least once each. Furthermore, it is very important to know specifically where these faults cross the river. There is the obvious reason that one needs to know where the levees may break in future

large earthquakes, but it is equally important to know how the Mississippi River and its flood plain will be altered.

Knowing that back thrusts probably cross the Mississippi River is not sufficient. We need to know specifically where they cross to predict how the river will be affected. For example, Figure 39 reveals that up-to-the-west displacement on the Reelfoot fault would produce a dam at the southern crossing, a waterfall (rapid) at the middle crossing, and a dam at the northern crossing. We also need to know exactly where the back thrusts cross the Mississippi River and its tributaries to predict how the rivers will be affected.

In addition to the fault crossings we must also consider the effects of uplift of the Tiptonville dome and Lake County uplift during a major earthquake. Clearly, uplift of the channel floor would be maximized over the Tiptonville dome with half that uplift amount occurring over the remainder of the Lake County uplift. The effects of such an uplift should be modeled. Specifically, a stream table model or computer simulations should vary tectonic uplift and river stage. The elastic rebound model of earthquake displacement suggests that there will also be net subsidence on the down-thrown sides of the faults. Thus, a major earthquake along the Reelfoot fault will displace and both positively and negatively warp the river profile, flood plain, and levees. If the Mississippi River were in flood stage during a major earthquake, breaching of the levees could occur. However, even if the river is not in flood during an earthquake, subsequent entrenchment across the Lake County uplift may undermine riprap and cause bank failures. Coseismic and post-seismic bank failure and post-seismic entrenchment would release sediment downstream that would affect river morphology.

Tectonic Geomorphology of the Upper Mississippi Embayment

Regional Uplift and Subsidence

The geomorphology of the upper Mississippi embayment is dominated by the Mississippi River valley and the loess covered hills east of the Mississippi River. Excellent discussions of the geomorphology of the Mississippi River Valley are presented by Autin et al. (1991), Saucier (1994), and Saucier et al. (1996). Tectonic geomorphology of the Mississippi River Valley was first extensively addressed by Fuller (1912) and subsequently by Russ (1982) where they identified areas of 1811-1812 coseismic uplift and subsidence within the valley. Areas of 1811-1812 and prehistoric Holocene uplift include the Lake County uplift, Tiptonville dome, Ridgely Ridge, southern Sikeston Ridge, and areas along the Blytheville arch at Marked Tree and Manila, Arkansas (Fig. 38) (Guccione et al., 1993; 1994; Guccione and Van Arsdale, 1995). Prehistoric and 1811-1812 subsidence areas include Reelfoot Lake, Big Lake, and Lake St. Francis (Fuller, 1912; Russ, 1982; Guccione and Van Arsdale, 1995). Van Arsdale et al. (1996) speculate that coseismic uplift of the Blytheville arch and perhaps subsidence northwest of the arch is responsible for damming of south-flowing drainage resulting in the "sunklands" of northeast Arkansas. Arch Johnston is currently studying old maps of the NMSZ, which may result in a better picture of 1811-1812 coseismic deformation.

The surface topography of the eastern bluffs of the Mississippi River Valley is particularly high and slopes easterly. Glenn (1906) and Wells (1933) believed the easterly slope was due to tectonic uplift of the bluff, perhaps coincident with the New Madrid earthquakes. Russ (1982) subsequently attributed this high ground and easterly slope to topographic inversion by erosion and the easterly thinning of the Pleistocene loess blanket. Saucier (1987) and Rodbell (1996)

identified easterly-sloping terraces along west-flowing Mississippi River tributaries in western Tennessee. They proposed that the terrace slope reversals are due to the easterly thinning loess blanket. However, Purser (1996) and Van Arsdale et al. (1996) document up-to-the-east faulting beneath the bluffs at Reelfoot Lake. Although there is no easterly dip revealed in the underlying Tertiary and Cretaceous strata beneath the bluffs, it does appear that faulting has locally controlled the eastern migration of the Mississippi River. Based on the presence of this bluff-margin fault, I speculate that other northeast-trending Mississippi bluff margins may be underlain by Reelfoot rift faults (Fig. 38).

The most prominent landforms in the Mississippi River Valley are Crowley's Ridge and Sikeston Ridge. As discussed above, faults lie beneath the margins of Crowley's Ridge (Van Arsdale et al., 1995a). It appears that Wisconsin arching, centered on Crowley's Ridge, resulted in eastern migration of the ancestral Ohio River east of the ridge, and western migration of the ancestral Mississippi River west of the ridge (Fig. 45). This lateral migration of the rivers away from the ridge during Wisconsin incision is responsible for the decreasing age of the terraces east and west of Crowley's Ridge.

Like Crowley's Ridge, Sikeston Ridge margins are underlain by faults. However, the structure beneath Crowley's Ridge is a horst and the major structure beneath Sikeston Ridge is a graben (Fig. 44) (Sexton, 1992). If Sikeston Ridge is soley erosional in origin, we would have to accept the fact that the erosional superposition of the ridge atop a graben is coincidental. I believe that this is highly unlikely and that Quaternary compression of the Sikeston graben resulted in uplift of Sikeston Ridge. If this is true, then the uplift must be Late Pleistocene or Holocene in age since the ridge is capped by Pleistocene ancestral Ohio river sediments (Saucier, 1974).

Dendrochronologic studies of Baldcypress at Reelfoot Lake reveal that the lake formed during the 1811-1812 earthquakes (Stahle et al., 1992; Van Arsdale et al., 1993; 1995b). A dramatic increase in tree-ring width occurred in the decade following 1812 along with a permanent reduction in wood density beginning in 1812 (Fig. 46). Uplift of the Tiptonville dome along the Reelfoot fault scarp appears to have resulted in the ponding of the west-flowing Reel Foot River. Coincident with the uplift was a 1 to 2 meter subsidence of the lake (Russ, 1982). Subsidence is supported by the observation that, if there were no net subsidence then Reelfoot Lake should have drained after breaching the fault scarp at Running Reelfoot Bayou - the natural drainage of Reelfoot Lake (Fig. 39). Similarly, at Big Lake and Lake St. Francis in northeastern Arkansas, it appears that portions of the Little River (Big Lake) and St. Francis River (Lake St. Francis) basins subsided while the Blytheville arch came up in 1811 (Fig. 38). At both Arkansas locations there is also evidence of prehistoric earthquakes revealed in sediment cores collected in and around the lakes (Guccione et al., 1993; Guccione and Van Arsdale, 1994; 1995). At Big Lake, a buried organic mat reflects 1811-1812 subsidence and an underlying organic mat reflects a prehistoric subsidence event. Cores at Lake St. Francis record four ponding events within the last 8,000 years. Dendrochronologic studies at Big Lake revealed no old Baldcypress; however, the dendrochronologic record at Lake St. Francis reveals only one major growth anomaly since A.D. 1321 and that is the growth suppression recorded in tree rings from 1813 to 1840 (Fig. 47) (Cleaveland and Stahle, 1994). Thus, it appears that any great earthquake that occurred on the southern arm of the NMSZ occurred over 490 years prior to 1811.

There are other areas that may have experienced subsidence. Work in progress by Johnston and Van Arsdale reveals that a lake formed on the Obion River in 1812 just upstream from where the Reelfoot fault has been recently projected to cross the river (Figs. 20 and 48). The Obion

lake, which no longer exists, therefore appears to have formed on the footwall of the Reelfoot fault.

Geomorphic analyses of the Mississippi Valley eastern and western lowlands has been conducted primarily through the study of river morphology of the Mississippi River and its tributaries (Fisk, 1944; Russ, 1982; Boyd and Schumm, 1995; Schumm and Spitz, 1996; Spitz and Schumm, 1997), and with detailed drainage analysis of the Lake County uplift (Merrits and Hesterberg, 1994). Russ (1982) documented warped Mississippi River levee profiles where the levees cross the Lake County uplift. Subsequently, Boyd and Schumm (1995) documented a decrease in channel depth and increase in channel width where the Mississippi River crosses the Lake County uplift (Figs. 49 and 50). Furthermore, Boyd and Schumm (1995) support Russ' (1982) interpretation that the western margin of the Tiptonville dome near river mile 882 and the western margin of the Lake County uplift near river mile 870 experienced down-to-the-southwest displacement during the 1812 earthquake. The steepest section of recent water-surface profiles is located at river mile 888 thus indicating that the nick point (historic waterfalls of Penick, 1981) that formed at river mile 882 in 1812, has migrated upstream 5 to 6 miles since 1812 (Boyd and Schumm, 1995).

Geomorphic analysis of the Mississippi River also suggests 1811 uplift of the Blytheville arch. Boyd and Schumm (1995) argue that Mississippi River profile data and seismic reflection data (Shedlock and Harding, 1982) reveal faulting at river mile 842 near Caruthersville, Arkansas (Fig. 49). Obermeier (1989) also noted a 21-foot thinning of Quaternary alluvium over the Blytheville arch.

Schumm and Spitz (1996) and Spitz and Schumm (1997) suggest that the Mississippi River

valley south of the NMSZ is also being influenced by Quaternary tectonics (Fig. 51). High sinuosity and steep valley slope occur at Reach 9 where the Mississippi River crosses the eastern boundary of the Reelfoot rift just northeast of the Crittenden County fault. Southwest of Memphis, Tennessee, the Mississippi River has a particularly straight course and appears to be warped as it passes over the Big Creek fault zone (Figs. 51 and 52) (Krinitzsky, 1950; Spitz and Schumm, 1997).

More subtle geomorphic expressions of tectonics are suggested in the topographic analysis of Mississippi River tributaries and drainage ditches (Boyd and Schumm, 1995; Spitz and Schumm, 1997). In the area of Catron, Missouri, near the northwestern termination of New Madrid seismicity, Boyd and Schumm (1995) suggest minor subsidence within the Little River drainage network. Boyd and Schumm (1995) also argue for minor warping along the Black River and near Pascola, Missouri. Further south, Spitz and Schumm (1997) cite geomorphic evidence for tectonic control of streams over the White River fault zone (Fig. 51). Similarly, these authors have suggested that plutons such as the Newport pluton have locally influenced drainage, thus suggesting Quaternary reactivation. Although these subtle geomorphic signals suggest tectonic control, detailed geologic studies are necessary to substantiate claims of Quaternary fault or pluton reactivation.

Landslides in the Mississippi Valley

According to Fuller (1912), one of the most spectacular products of the 1811-1812 New Madrid earthquakes were the landslides along the eastern Mississippi Valley bluffs from Cairo, Illinois, to Memphis, Tennessee (Fig. 53) (Jibson and Keefer, 1988). The average bluff height in Figure 53 is 120 feet with maximum heights of 225 feet. Stratigraphy exposed in the bluffs

in Tennessee consists of Eocene Jackson Formation (Eocene Claiborne Formation in Kentucky), overlain by Plio-Pleistocene Lafayette Formation (Upland Gravel), and capped by Pleistocene Loess (Fig. 54). Since the top of the Jackson and Lafayette formations are both unconformable, the thicknesses of the exposed sections vary. Jackson exposure thicknesses are as great as 150 feet, Lafayette from 0 to 65 feet, and loess from 10 to 150 feet. As indicated in Figure 54, the Jackson Formation dips westward into the valley towards the axis of the Mississippi embayment and the overlying Lafayette is essentially horizontal.

Jibson and Keefer (1988) mapped 221 large landslides ($\geq$ 200 feet long) of three distinct types; coherent translational and rotational block slides, earth flows, and young slumps along actively eroding banks. The detachment surface is in a Jackson clay layer near the base of the bluff (Fig. 55). Based on geologic and engineering analyses, Jibson and Keefer (1988; 1992) concluded that the coherent slides and most of the earth flows were caused by the New Madrid earthquakes of 1811-1812.

Although not well documented, extensive landsliding is also present along the eastern margin of Crowley's Ridge (Ding, 1991). I am not aware of any landslides along the margins of Sikeston Ridge although they should exist.

Loess Craters in Northwestern Tennessee

Circular depressions (craters) exist in the loess-covered bluffs of northwestern Tennessee (Morse, 1941; Dennen, 1990). A total of 53 craters are located in an 80 km^2 area that includes the Samburg, Hornbeak, and Ridgely 7.5 minute quadrangles east of Reelfoot Lake (Fig. 56) (Dennen, 1990). The craters range in diameter from 50 to 150 m and are up to 3 m deep.

Their origin is not known; however, proposed modes of origin include liquefaction, piping, deflation, meteorite impact, periglacial origin, sinkholes, depressions on an underlying bog surface, or buffalo wallows. If indeed the crater distribution is as limited as described by Dennon (1990) then I believe that we can rule out piping, deflation, sinkholes, periglacial processes, buffalo wallows, or depressions on an underlying bog surface. Since the craters appear to occur atop and immediately adjacent to the Reelfoot and Ridgely faults I believe that their origin is probably seismic. I propose two possible origins: 1) uplift of the Reelfoot fault and possibly the Ridgely fault may have locally formed and/or opened joints within the loess that promoted piping, or 2) severe ground shaking may have generated high air pressure within the small pore spaces of the loess which was explosively released upon breaking through a surface soil B horizon. If the craters are due to expulsion of loess (model 2), then there should be a buried soil profile around the rim of the craters.

Discussion of Tectonic Geomorphology of the Upper Mississippi Embayment

Controversy remains as to the distribution of 1811-1812 coseismic deformation. This is important to our evaluation of the integrity of engineered structures within the upper Mississippi embayment. Obviously, a repeat of the 1811-1812 sequence would strongly affect the geometry of the Mississippi River, its tributaries, and the extensive drainage system in the Mississippi Valley. Since Reelfoot Lake, Big Lake, and Lake St. Francis have a history of subsidence, then we can assume that areas of subsidence and uplift will continue to deform in a similar way, at least through the next earthquake sequence. Gomberg (1992; 1993) has analyzed 1811-1812 deformation as plane strain in a horizontal strain field (Fig. 57). Gomberg and Ellis (1994) subsequently treated the problem as a 3-dimensional strain field. In these mathematical studies the investigators have assumed a system of faults and then slipped

them to create a strain field. They then compared the calculated strain field with the observed strain field - the areas of subsidence and uplift. Although this is instructive, I believe that we should define the 1811-1812 strain field and then find the combination of faults and fault displacements that best fit that strain field. This approach is in progress. Arch Johnston is compiling old maps to try and determine the topography caused by the 1811-1812 earthquakes. A second approach to this problem should be attempted using digital elevation model (DEM) data. I believe that it may be possible to discern areas of tectonic uplift and subsidence by mathematically passing a first order trend surface (the idealized Mississippi River floodplain surface) through the landscape and map the residuals. Essentially, this is the approach that Russ (1982) used to map the Lake County uplift. With today's computer software and DEM data it should be possible to do it throughout the Mississippi River valley.

Dendrochronology is a very under-used tool in paleoseismology of the upper Mississippi embayment. The work of Stahle et al. (1992) and Cleaveland and Stahle (1994) has clearly shown a tree-ring signal of the 1811-1812 earthquakes. David Stahle has Baldcypress tree ring indices to A.D. 1677 at Reelfoot Lake; however, there are living Baldcypress trees in the lake that are over 1000 years old! I believe that additional Baldcypress dendrochronology studies of Reelfoot Lake would result in valuable paleoseismic data.

The geomorphological literature review supports the need for more strain field and dendrochronology research but it also suggests additional research projects should be undertaken. For example:

1. Trenches should be excavated across the margins of Sikeston Ridge to determine if it has been uplifted in Quaternary time. If so, Sikeston Ridge is a potential seismic source zone.
2. More seismic reflection work should be done at the southern margins of Big Lake and Lake St.

Francis to determine if there was coseismic uplift of the Blytheville arch in 1811.

3. Boyd and Schumm (1995) state, "Downstream of Island 11, both the flood-plain and levee profiles steepen sharply. Russ (1982) showed that a maximum of 2 m of uplift is recorded by the warped profiles. The post-1820 flood-plain profile steepens between Island 11 and Tiptonville. This steepening of the recent landform may reflect recent, or perhaps ongoing, flood-plain deformation in that reach (Russ, 1982)." This proposed post-1820 warping should be verified. If the warping is post-1812, then it is a measure of strain accumulation and would be valuable in predicting the next earthquake on the underlying Reelfoot fault.

4. Most landslides along the Mississippi Valley bluffs in Tennessee formed during the New Madrid earthquakes. Thus, prehistoric earthquakes may have caused landslides. Sediment ponding is evident in some first order streams along the bluff line. Apparently, the slide blocks have disrupted (ponded) the drainage. Coring through the floodplains of these first order streams may result in the identification of pre-1811 ponding (seismic) events.

5. The Big Creek fault zone has 17 m of Quaternary displacement at Helena, Arkansas (Krinitzsky, 1950), and thus may be a seismic source zone. This fault should be trenched to determine its detailed Quaternary history and it should be traced to the northeast since it may extend to Memphis, Tennessee.

Earthquake Surface Rupture and Liquefaction in the Upper Mississippi Embayment

Reelfoot Fault

Although the 3 great earthquakes of 1811-1812 had moment magnitudes of 8.1, 7.8, and 8.0, the only known surface fault is the Reelfoot reverse-fault scarp (Fig. 58). Apparently, the

first and second events occurred on strike-slip faults, thereby leaving no scarps. Trenches excavated across the Reelfoot scarp have revealed an east-facing monocline broken by normal faults, reverse faults, and sand dikes (Fig. 59). Russ (1979; 1982) first excavated a trench across the scarp and concluded that there had been 3 faulting events within the last 2,000 years. Subsequently, a better dated earthquake chronology has been interpreted from scarp-derived colluvium at the Champey Pocket trench (Kelson et al., 1992) and from graben-fill sediments at the Proctor City trenches (Kelson et al., 1996) (Fig. 58). Three faulting events have occurred along the Reelfoot scarp within the last 2,400 years; between A.D. 780 and 1000, between A.D. 1260 and 1650, and during A.D. 1812. Thus, the recurrence interval of the Reelfoot fault is estimated to be 400-500 years (450 years) (Kelson et al., 1996).

Another trench site is scheduled to be opened in September of 1997 at New Madrid, Missouri. The New Madrid site may provide evidence for earlier faulting since the surface sediments are believed to be older at this site.

Liquefaction (Sand blows) within the Upper Mississippi Embayment

Historical accounts of the great New Madrid earthquakes document sand, water, and wood (lignite) shooting out of the ground in great fountains (Fuller, 1912; Penick, 1981). Craters and linear fissures hundreds of meters long and up to 6 m deep opened across the landscape. The severe ground shaking increased ground water pressure in the saturated Mississippi River sands (sand bars) beneath a thin clay cap (overbank clay). The high water pressure overcame the strength of the clay cap, and liquefied sand explosively vented (blew) to the surface where it accumulated as circular mounds of light sand over dark clay. Deposits from these sand blows are still clearly visible in the fields of northeastern Arkansas and southwestern Missouri,

particularly from the air (Figs. 60 and 61) (Fuller, 1912; Obermeier, 1984; 1988; 1989). The sand blow deposits occur over 10,000 km^2 and in large areas covers more than 25% of the land surface (Fig. 60). Fuller (1912) noted that the average sand blow deposit was domal, 3 to 6 inches thick, and 8 to 15 feet across (Fig. 62). However, agricultural practices have apparently destroyed most of the small sand blow deposits so that today typical sand blow deposits are 1.0-1.5 m thick and 10-30 m in diameter (Schweig and Van Arsdale, 1996).

Where the clay cap is thin, sand blows tend to be more closely spaced and smaller. Explosive liquefaction also occurred where there was no clay cap. In these areas it appears that a weakly cemented sand provided the cap. The liquefaction features in the areas of the sand cap were primarily large open craters like those documented in the 1886 Charleston, South Carolina earthquake (Obermeier, 1996).

Many sand blow deposits occur along linear surface fissures and even the circular sand blow deposits are connected by sand dikes at shallow depth (Obermeier, 1996). Fuller (1912) noted that linear sand blows are commonly associated with tectonic fissures and lateral spreads along river courses. The dikes are sand filled, planar, dip from 60 to 90 degrees, and range in width from millimeters to several meters. Where the dikes are several centimeters thick they typically are spaced several meters to hundreds of meters apart (Obermeier, 1996). The clay cap may be folded down along the dike margin apparently due to subsidence. At a bigger scale, Schweig et al. (1992) have noted subsidence of the ground surface adjacent to sand dikes, apparently due to sand withdrawal at depth (Fig. 63).

Sand sills, although not visible at the surface, are a major liquefaction feature (Fig. 64). The sills form primarily along the base of the clay cap, along bedding planes, and beneath strong

root mats (Obermeier, 1996). Sill thickness is variable but may be as great as 0.7 m near the surface. Angular clay-rich clasts commonly found within Mississippi Valley sills suggest that the sills were explosively injected. Laccolithic intrusions of the sills locally form circular and elongate bulges on the ground surface (Obermeier, 1996).

Paleoliquefaction has been a particularly powerful tool in deciphering the paleoseismology of the upper Mississippi embayment (Tuttle and Schweig, 1995; 1996; Tuttle et al., 1996; Schweig and Van Arsdale, 1996). Paleoliquefaction sites are located within the NMSZ and in the Western Lowlands (Fig. 65). Paleoliquefaction studies in the Western Lowlands of Missouri has identified 4 paleoseismic events dating from 23,000-17,000 B.P., 13,430-9000 B.P., A.D. 240-1020, and A.D. 1440-1540 (Vaughn, 1991; 1992; Vaughn et al., 1993). Vaughn speculates that the seismic source of the Western Lowland earthquakes may have been the Commerce fault, a fault beneath the western margin of Crowley's Ridge, or the NMSZ. Studies within the southern portion of the NMSZ reveal a minimum of 3 paleoliquefaction events in the 2,000 years prior to 1811 (Fig. 66) (Schweig and Van Arsdale, 1996). These events are believed to have occurred between A.D. 0-500, A.D. 800-1000, and A.D. 1200-1400. At the northern end of the NMSZ, paleoearthquakes have been dated at approximately A.D. 439, A.D. 539-911, and A.D. 770-1020.

Discussion of Liquefaction in the Upper Mississippi Embayment

The extensive 1811-1812 liquefaction and paleoliquefaction demonstrates that future liquefaction is a major threat to the engineering integrity of the upper Mississippi embayment. Obermeier (1996) estimates that even moderate earthquakes with magnitudes of 6.4 can cause liquefaction in the embayment. Where there is no clay cap, liquefaction may temporarily

change sandy soil to quicksand. This quicksand condition is conducive to the sinking of high density structures (buildings, bridges, transmission towers and poles, ect.) and the floating to the surface of low density structures (pipe lines, gasoline tanks, septic tanks, coffins, etc.). In areas where a clay cap may not permit surface quicksand, the ground may still subside and be covered by sand (Figs. 60 and 63). Structures may actually localize liquefaction as the saturated sand moves up through the clay cap around poles or footings.

The surface liquefaction of 1811-1812 is very impressive. We must also realize that for every vent or fissure there must be over 10 times as much underlying injection. Most people would agree that the combined effects of ground rupture, ground roll, and liquefaction from a magnitude 8 earthquake on the NMSZ would destroy buried life lines and severely damage surface structures in the zone of liquefaction demarcated in Figures 60 and 65. However, there is a perspective to this gloomy prediction that needs to be considered. Liquefaction is optimum in saturated, unconsolidated, sand. Those conditions were clearly present in 1811-1812. However, the water table is now lower for much of the NMSZ because of drainage ditches, river levees, and pumping for irrigation. Perhaps we have locally diminished liquefaction susceptibility by lowering the water table.

The water table is, of course, not lower along the Mississippi River levees. Although the thickness of the levee material should inhibit venting beneath the levees it is not clear to me what would happen along the margins of the levees. In particular, where clay was removed from the adjacent landscape for levee construction the clay cap is thinned and surface venting would probably be promoted. I also question whether the levees affect local pore pressure and if so how will they affect pore water pressure buildup during an earthquake.

The Forces Responsible for Earthquakes in the Upper Mississippi Embayment

Perhaps the most intriguing question of the NMSZ is what is causing the earthquakes? Although stress orientations vary somewhat around the NMSZ (Fig. 67), the average stress field east of the Rocky Mountains is a maximum horizontal principal stress oriented N60°-65° E and a vertical intermediate principal stress (Zoback and Zoback, 1989; Zoback, 1992). The regional stress orientation is conducive to right-lateral strike slip movement on northeast-striking vertical faults (N50°E oriented Reelfoot rift faults) and left-lateral strike-slip movement on northwest-striking vertical faults. However, the magnitudes of the intermediate and minimum stresses are quite close and so thrust faulting is common in the mid continent.

The source of the intraplate stress field has been attributed to body forces acting on a high-density rift pillow beneath the lower crust of the Reelfoot rift (Ervin and McGinnis, 1975; Grana and Richardson, 1996) and/or to plate tectonic stresses (Sbar and Sykes, 1973; Sykes, 1978; Herrmann, 1979; Zoback and Zoback, 1989). Proposed plate tectonic stresses include basal viscous drag of the asthenosphere on the lithosphere, slab pull from subduction zones, with most researchers favoring plate push from the plate's divergent margin (Richardson, 1992; Zoback, 1992). In the case of the North American plate and the NMSZ, our stress field is due to pushing from the mid Atlantic Ridge. Schweig and Ellis (1994) have argued that the NMSZ has undergone a rotation of its stress field within the last 3 million years thereby essentially "turning on" the current seismicity (Fig. 68). However, since the mid Atlantic Ridge has not changed position and the magnetic seafloor stripes are of uniform width since the Cretaceous, it appears that the North American intraplate stress orientations have been generally uniform at least since the Cretaceous. I believe the stress field rotation hypothesis should be more thoroughly examined.

Schweig and Ellis (1994) and Pratt (1994) point out that the low topography and absence of major structural deformation indicates that the upper Mississippi embayment has undergone little total strain since the Late Cretaceous. Late Cretaceous strata are essentially flat in the Mississippi embayment. Perhaps the reason we do not see much displacement on the top of the Cretaceous section at any one location is because deformation in the upper Mississippi embayment moves from area to area through time. This migration of deformation is suggested in the different ages of deformation in Crowley's Ridge, Benton Hills, Sikeston Ridge, and the NMSZ.

Schweig and Van Arsdale (1996) advocate that the NMSZ is currently experiencing a pulse of activity, and that the NMSZ may have been seismically dormant for many thousands of years prior to the Quaternary. If this turning on and off of faults within the upper Mississippi embayment is true, then it suggests fluctuations in stress or fault strength within the embayment. The following is an outline of possible mechanisms.

A. Mechanisms by which the upper Mississippi embayment stress field might fluctuate.

1. Episodic changes in North American plate motion.
2. Episodic increases in spreading rates at the mid Atlantic Ridge.
3. Changes in the vertical principal stress by:
    a. Advance and retreat of continental glacier forebulges.
    b. Erosion and deposition by the Mississippi River.
    c. Eustatic sea level changes.
4. Episodic local intrusion.
5. Episodic changes in fault zone pore pressures (Zoback and Zoback, 1992).

B. Mechanisms by which fault zones may weaken.

1. Metamorphism or replacement of fault zone rocks to mechanically weaker gouge rocks.

2. Solutioning of rocks and karstification of fault zones.

Discussion of Forces Responsible for Earthquakes in the Upper Mississippi Embayment

Forces working on the upper Mississippi embayment are better addressed by Geophysicists. However, I wish to make some geologic observations. Seismicity in the NMSZ represents a snapshot in time. Perhaps, over longer periods of time, fault zones might seismically light up at various locations throughout the mid continent. Within the geoscience literature much is made of the Reelfoot Rift as controlling seismicity within the embayment. However, there are other major rifts in North America, like the mid continent rift, that are seismically quiet (Fig. 67). So what makes the Reelfoot rift apparently unique. Cox and Van Arsdale (1997) point out that a mantle plume has passed beneath the Mississippi embayment and Charleston, South Carolina, and a second plume has passed beneath the St. Lawrence River seismic zone since Cretaceous time and perhaps that is an important factor. However, the most striking aspect of the NMSZ is that it is overlain by a major river system - the Mississippi River. Much current work is addressing the interaction of tectonics and surficial processes with an entire volume of the Journal of Geophysical Research dedicated to the subject (Ellis and Merritts, 1994). I believe that the periodic faulting activity within the Mississippi embayment may be directly related to the history of the Mississippi River. As one example, it appears that Crowley's Ridge was tectonically rising when the ancestral Mississippi and ancestral Ohio Rivers were flowing down both sides of it. Was the diversion of the ancestral Mississippi River to the eastern side of Crowley's Ridge merely a consequence of uplift of Crowley's Ridge or was shifting of the river

position responsible for shutting down the uplift of the ridge? As we become more knowledgeable of the tectonic and fluvial history of the upper Mississippi embayment it will be interesting to compare their chronologies. In the mean time, it should be possible to undertake numerical studies to determine the effects (if any) of erosion and deposition within the Mississippi Valley as stress inducers to seismicity.

Conclusions

Precambrian rifting appears to have set the stage for subsequent deformation within the Mississippi Valley. Precambrian mid continent drainage probably looked very much like it does today with a major river flowing southward within the Reelfoot rift into the ancestral Gulf of Mexico. Paleozoic through Mesozoic sedimentation and deformation within the rift probably was significant but was largely destroyed by mid-Cretaceous uplift and erosion of the Mississippi Valley arch as the area passed over the Bermuda hotspot. The preserved history resumes with late Cretaceous and Tertiary subsidence of the arch and the formation of the Mississippi embayment; a consequence of thermal cooling as the continent moved westward off of the hotspot. Late Tertiary uplift of the upper Mississippi embayment resulted in the absence of Oligocene and Miocene sediments. The youngest Tertiary sediments within the upper Mississippi embayment are the Upland Gravels of probable Pliocene-Pleistocene age. The Upland Gravels and all Quaternary fluvial sediments are erosionally inset into Eocene sediments of the upper Mississippi embayment. Thus, the Mississippi River has been entrenching during the latter part of the Pliocene Epoch and during all of the Quaternary Period. Whether this entrenchment is due to sea level lowering or tectonic uplift is not clear. If indeed the entrenchment is due to regional uplift of the upper Mississippi embayment, then the uplift may be locally manifested as Quaternary fault displacement like that documented in this report.

Effects from the New Madrid earthquakes of 1811-12 were catastrophic and widespread within the Mississippi River valley. Trench studies of the Reelfoot fault and paleoliquefaction studies reveal that there have been at least 4 large earthquakes within the last 2000 years within the NMSZ. When paleoliquefaction is more fully studied in the Western Lowlands the chronology may be extended for the NMSZ or additional western seismic sources may be defined. More data are necessary to better constrain the dates and magnitudes of prehistoric earthquakes but it appears that the recurrence interval for large earthquakes that cause surface faulting is about 450 years for the Reelfoot fault and the NMSZ in general. Since there has been no apparent change in the mid-continent stress field since 1812, we can assume that there will be damaging earthquakes in the Mississippi Valley in the future.

Johnston (1996) has estimated moment magnitudes of 8.1, 7.8, and 8.0 for the three 1811-12 main shocks. Johnston and Schweig (1996) propose various faulting scenarios (Fig. 69). The different scenarios conclude that there was a main shock either along the Bootheel lineament or along the Blytheville arch, the second main shock occurred on the northern arm of seismicity near New Madrid, and the last main shock occurred along the Reelfoot fault. Purser (1996) has noted that the displacement histories of the Reelfoot fault and Ridgely faults (Blytheville arch) have been very similar and speculated that these faults are linked. If true, then the three main shocks of 1811-12 were not unique and we can expect a three main shock sequence during the next major New Madrid event.

The Reelfoot fault crosses the Mississippi River at three locations and its hanging wall back thrusts cross the river at least once each. During a large earthquake this fault system will break the levees, permanently warp the ground surface, and at least temporarily warp the river bed profile. Thus, this fault system is most likely to cause permanent deformation on the

Mississippi River during an earthquake. The areas of uplift and subsidence, like the Lake County uplift and Big Lake, should continue to deform in a similar way during future earthquakes. It is desirable to have better maps indicating the 1811-1812 strain field so that the Corps can determine which ditches within the drainage network will require cutting or filling after an earthquake. Landslides along the eastern margins of the Mississippi Valley, Crowley's Ridge, and perhaps both margins of Sikeston ridge will occur but there is apparently little threat to Corps structures. A major seismic threat to Corps structures within the Mississippi Valley is liquefaction. The 1811-1812 liquefaction was so intense and occurred over such a large area that it is truly frightening to think of it occurring today. Tests should be undertaken to determine the liquefaction vulnerability of the Mississippi River levees and the effect of a lower water table as a possible liquefaction deterrent at critical facilities.

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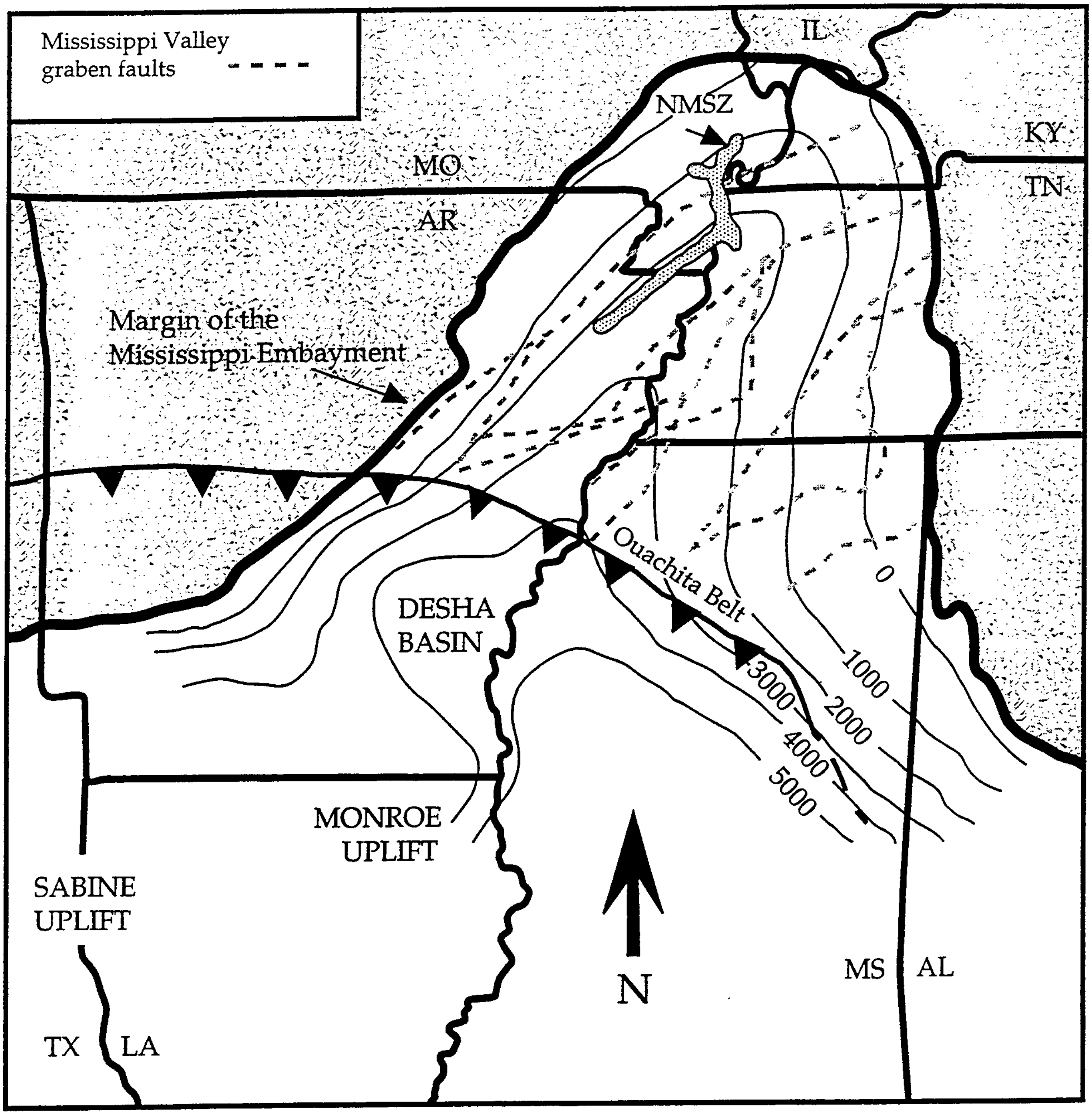


Figure 1. The New Madrid seismic zone (NMSZ) within the upper Mississippi Embayment. From Cox and Van Arsdale, 1997.

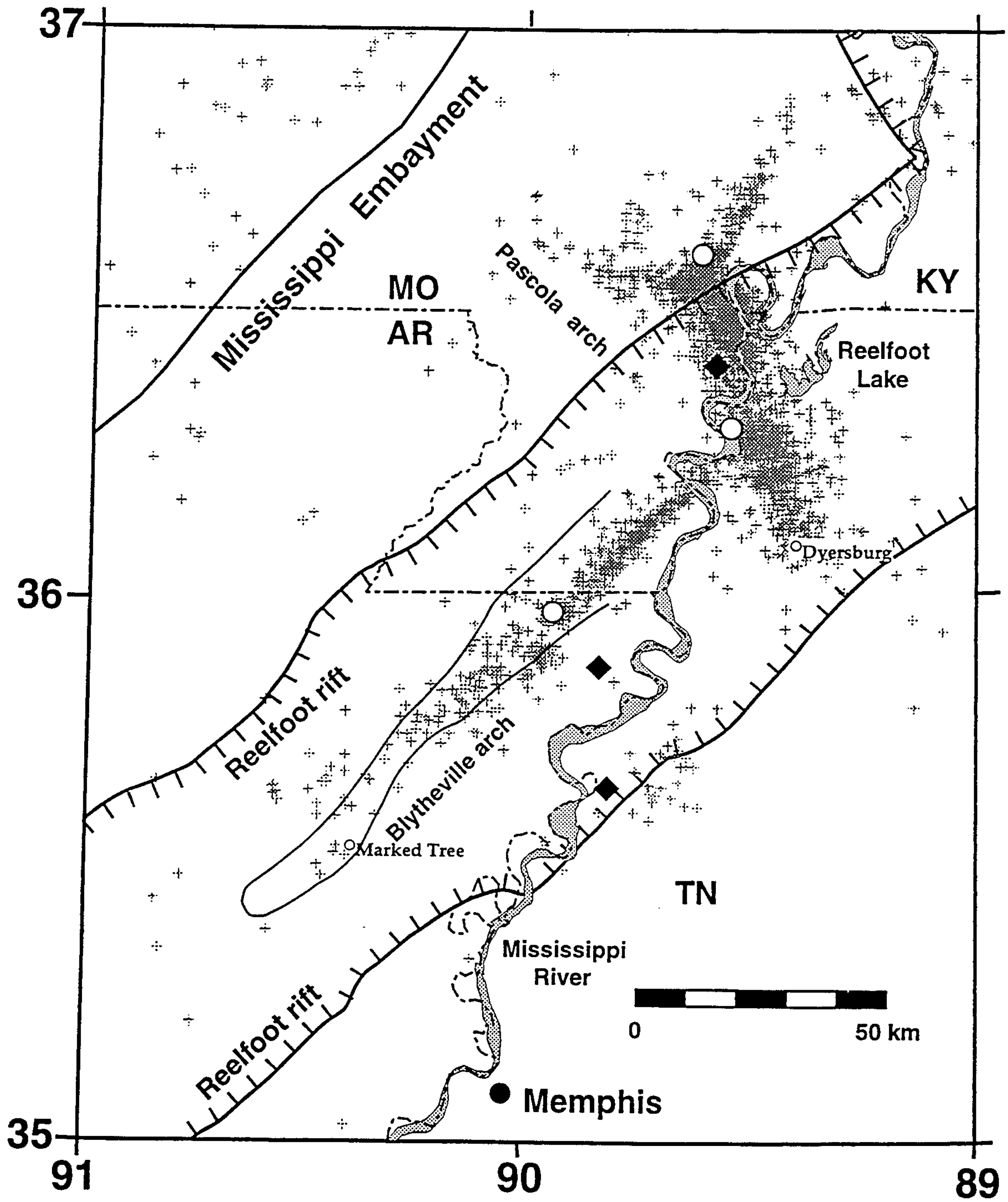


Figure 2. Microseismicity of the New Madrid seismic zone indicated with crosses. The open circles represent the locations of the 3 major shocks of 1811 and 1812. Black diamonds are key wells. The northern well is the New Madrid test well, central one is the Wilson well, and southern one is the Fort Pillow well.

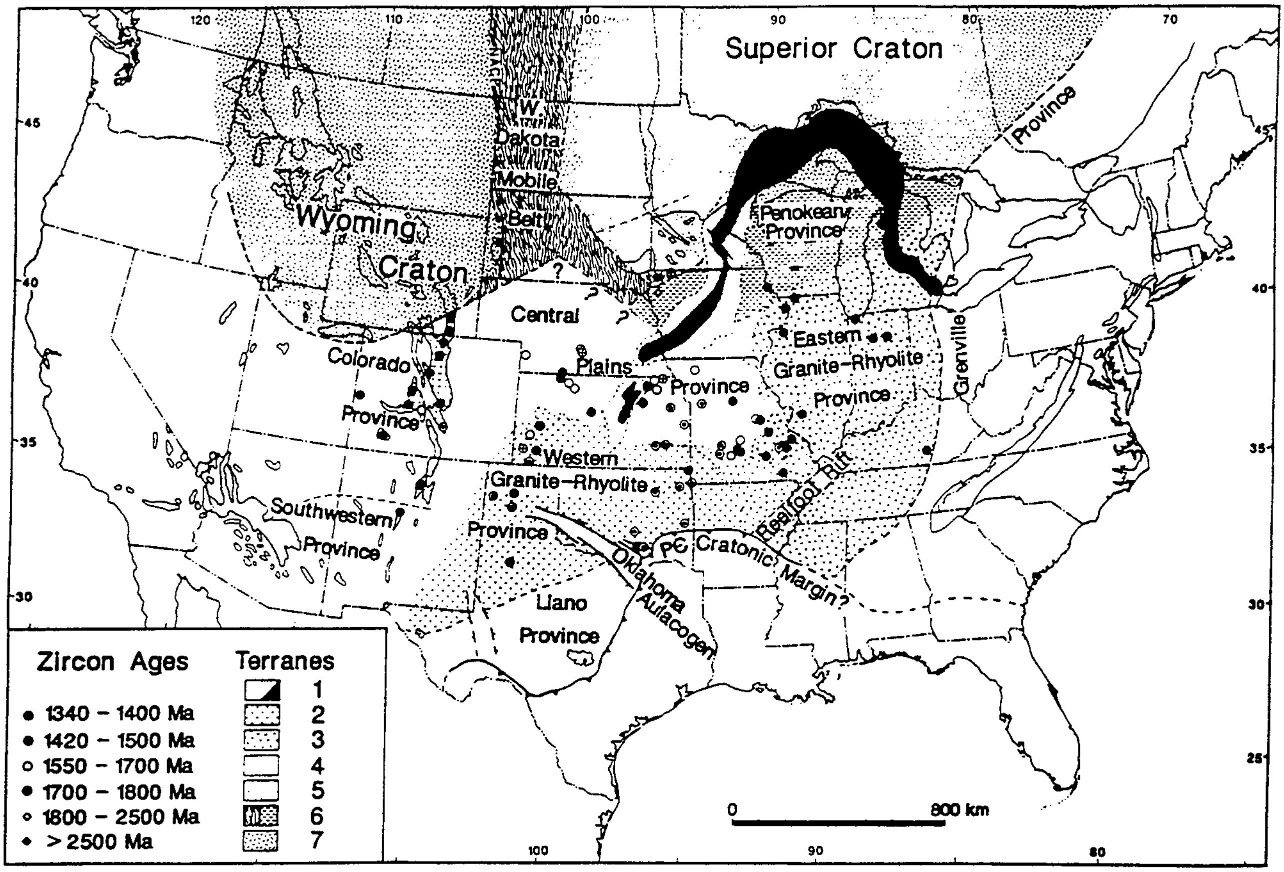


Figure 3. Generalized geologic map for Precambrian basement of central United States, showing major tectonic and petrologic provinces. Terrane 1 is midcontinent rift system; other terranes as named on map. From Bickford, 1988.

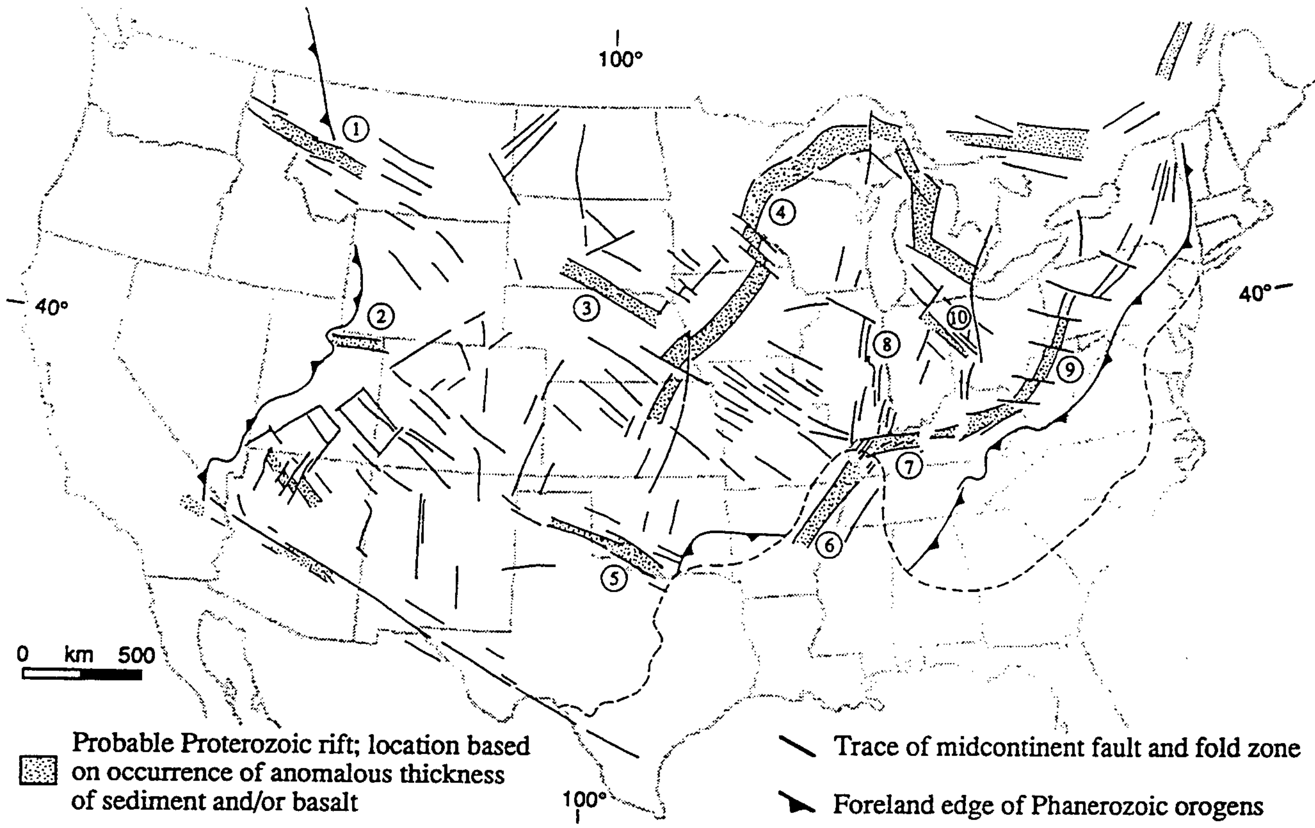


Figure 4. Regional map illustrating distribution of principal U.S. midcontinent fault and fold zones. 1-Helena embayment, 2-Uinta trough, 3-Nebraska sag, 4-Midcontinent rift, 5-Southern Oklahoma aulacogen, 6-Reelfoot rift, 7-Rough Creek graben, 8-La Salle deformation belt, 9-Rome trough, 10-Fort Wayne rift. From Marshak and Paulsen, 1996.

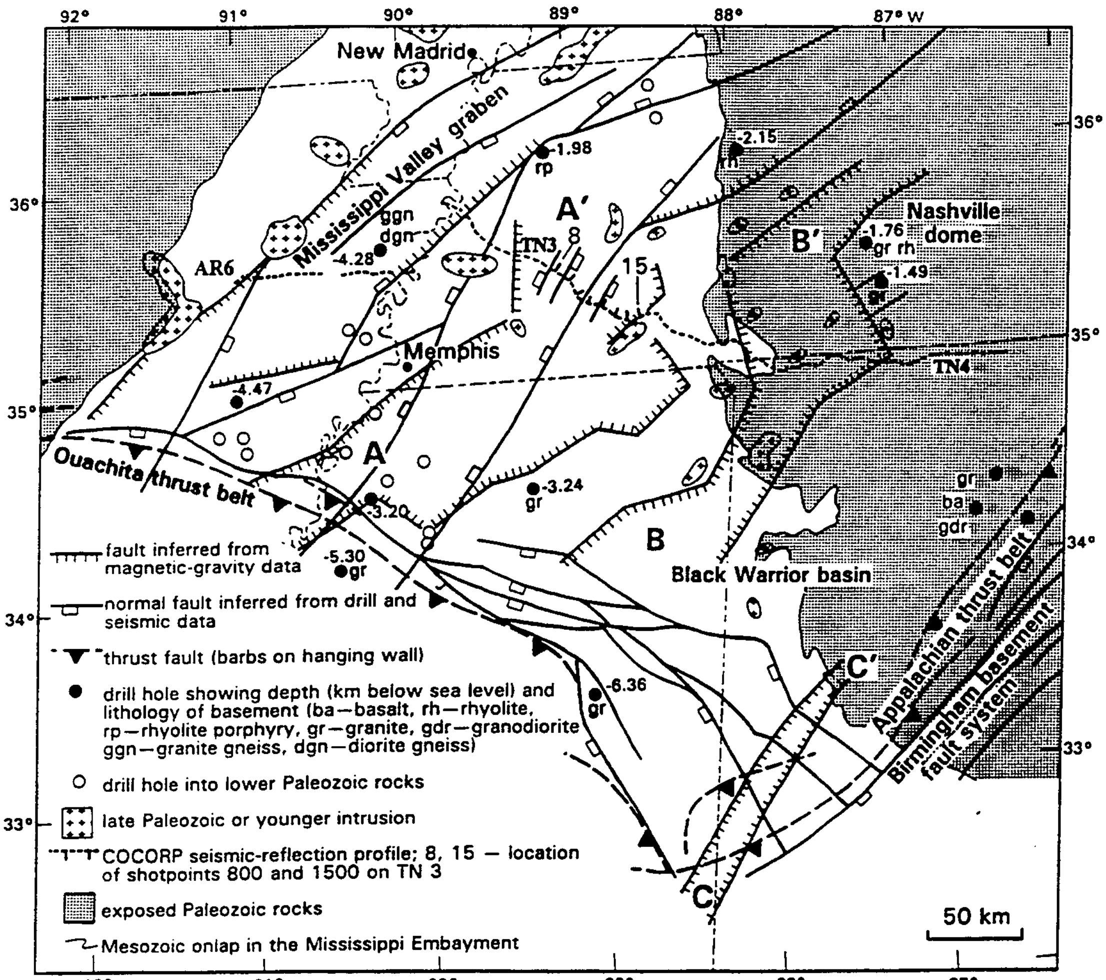


Figure 5. Basement and Paleozoic faults beneath Mississippi embayment in Mississippi, Alabama, and Tennessee mapped from drill and seismic data and potential-field data, and late Paleozoic or younger intrusions. Inferred grabens A-A', B-B', and C-C' are drawn on basis of combined interpretation of magnetic and gravity data. Symbols for faults inferred from magnetic and gravity data and from drill and seismic data are combined where such faults coincide. From Johnson et al., (1994).

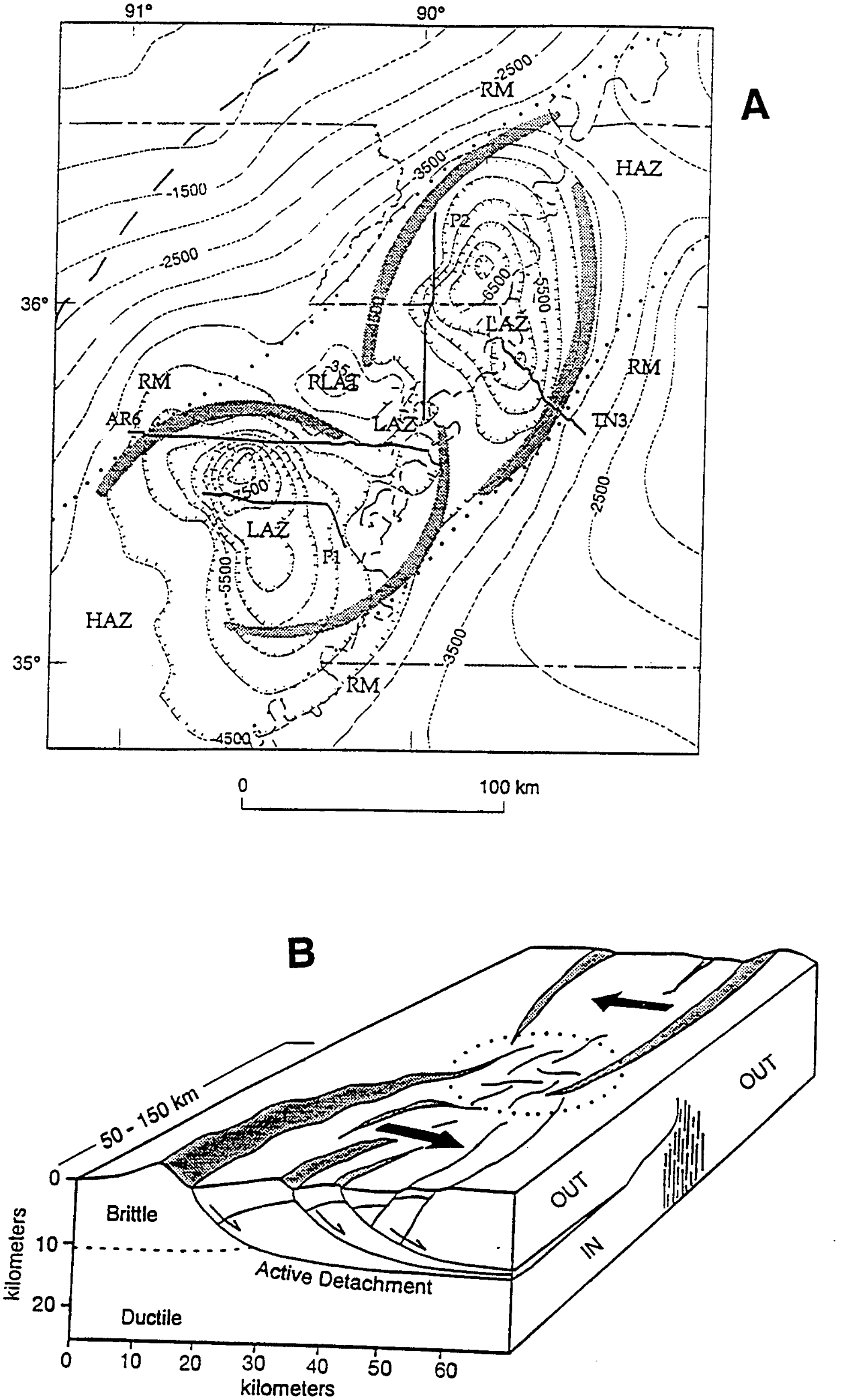


Figure 6. A. Contour map of the Reelfoot rift basement showing the speculative distribution of half-graben features such as the areas of half-graben border faulting (shaded arcs), the rift platform (PLAT), and the high-relief and low-relief accommodation zones (HAZ and LAZ, respectively). The locations of COCORP AR6 and TN3 and U.S. Geological Survey P1 and P2 seismic-reflection lines are shown. The dotted lines indicate the reinterpreted rift margins using the half-graben faulting model and the contour-gradient inflections. The margin of the Mississippi embayment is shown as a dashed line. Contour interval is 500 m.
B. Schematic diagram of extensional continental rifting under low strain conditions showing half-graben faulting, detachment polarity reversal, and an accommodation zone (dotted line) with overlapping and converging half-graben border faults. From Dart and Swolfs, in press.

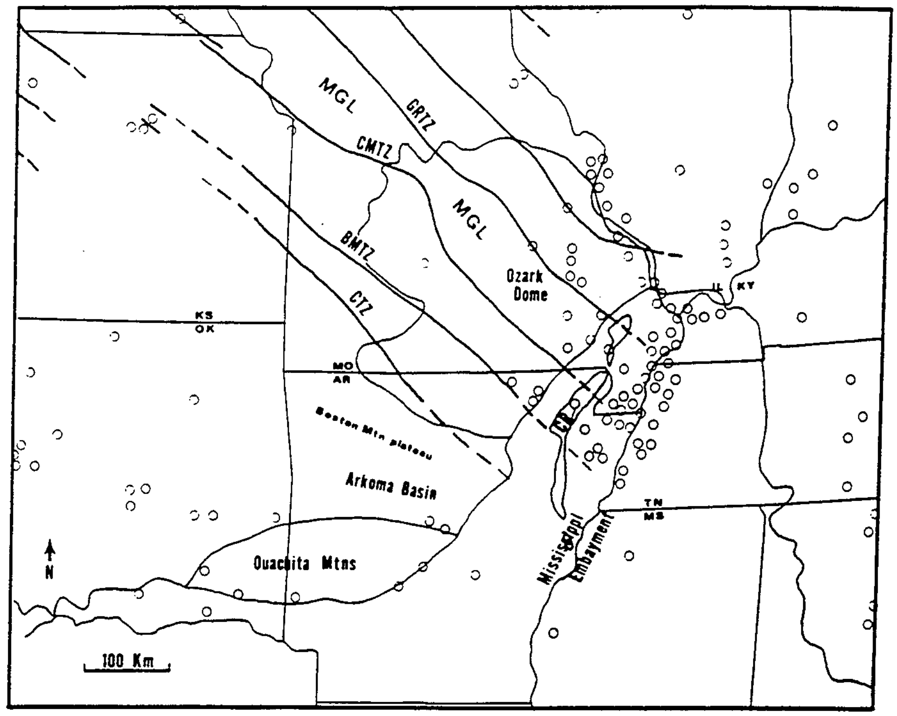


Figure 7. Major early Proterozoic basement fault zones of Midcontinent region. CTZ = Chesapeake Tectonic Zone; BMTZ = Bolivar-Mansfield Tectonic Zone; CMTZ = Central Missouri Tectonic Zone; GRTZ = Grand River Tectonic Zone; CR = Crowley's Ridge; MGL = Missouri Gravity Low. Open circles are earthquake epicenters (1928-1971). More recent earthquake data (including large numbers of microearthquakes) are not shown in order to avoid obscuring the features discussed. From Cox, 1988b.

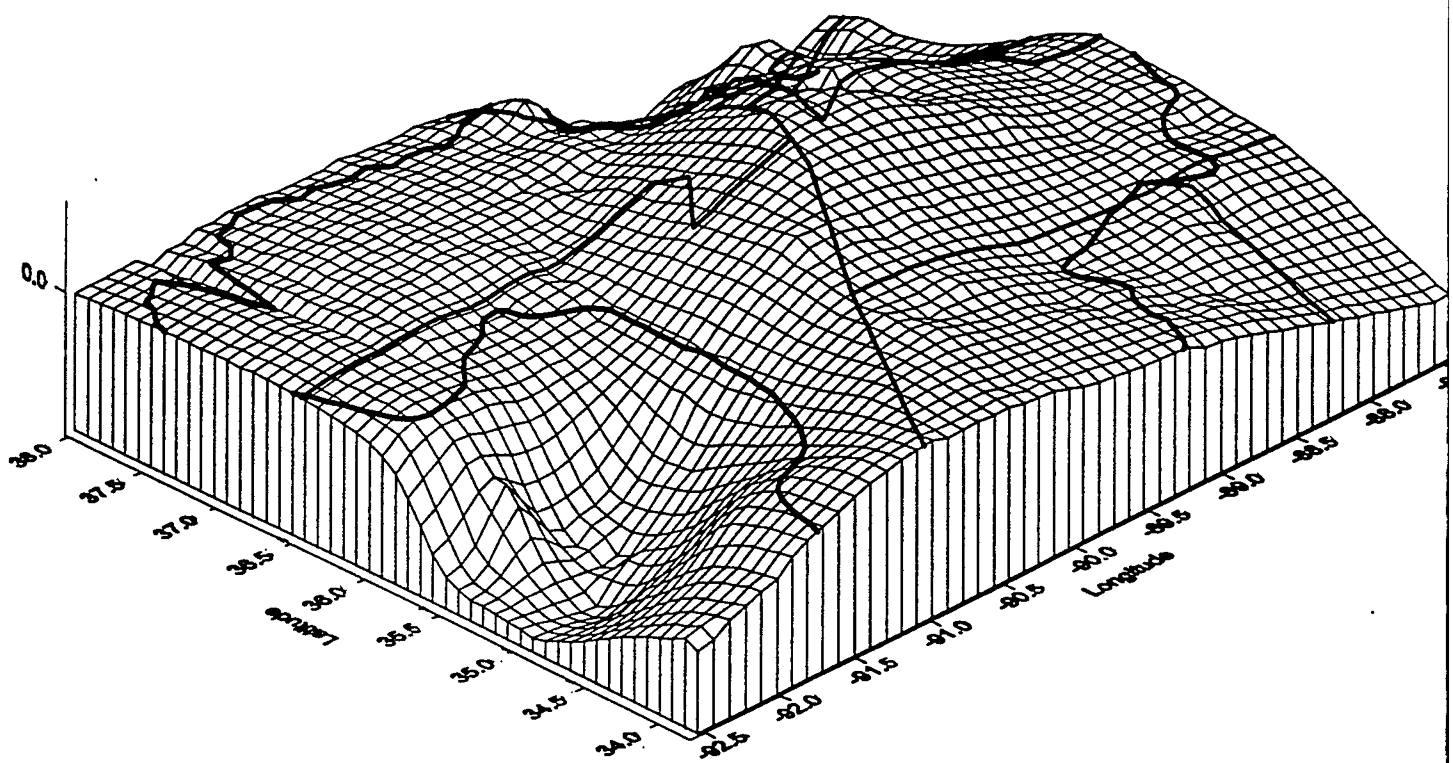


Figure 8. A three-dimensional view of the Chattanooga surface at mid-Cretaceous time looking northeast from the Ouachita orogenic front. From Cox and Van Arsdale, 1997.

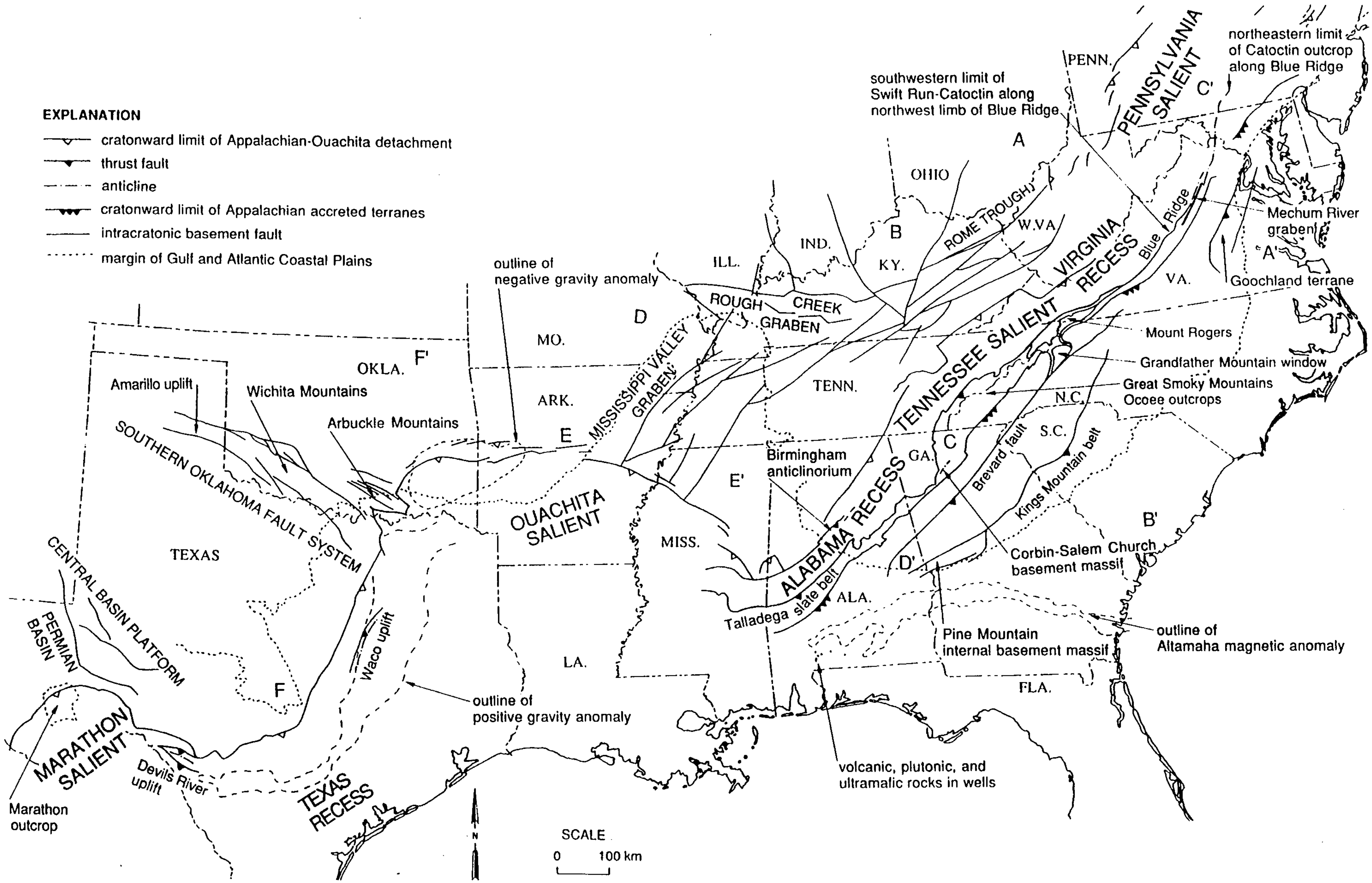


Figure 9. Outline map of Appalachian-Ouachita orogenic belt and intracratonic fault systems. Locations of rift-related rocks are shown in present structural position. End points of cross sections are indicated by letters. From Thomas, 1991.

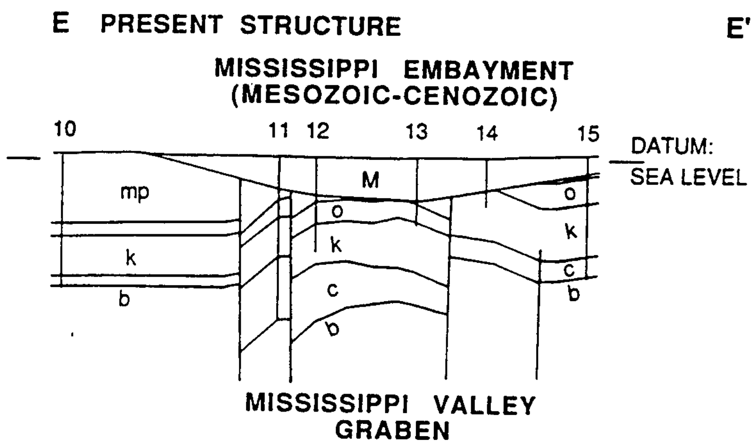


Figure 10. Structural cross section of the Mississippi Valley graben fault system. See Figure 9 for location. From Thomas, 1991.

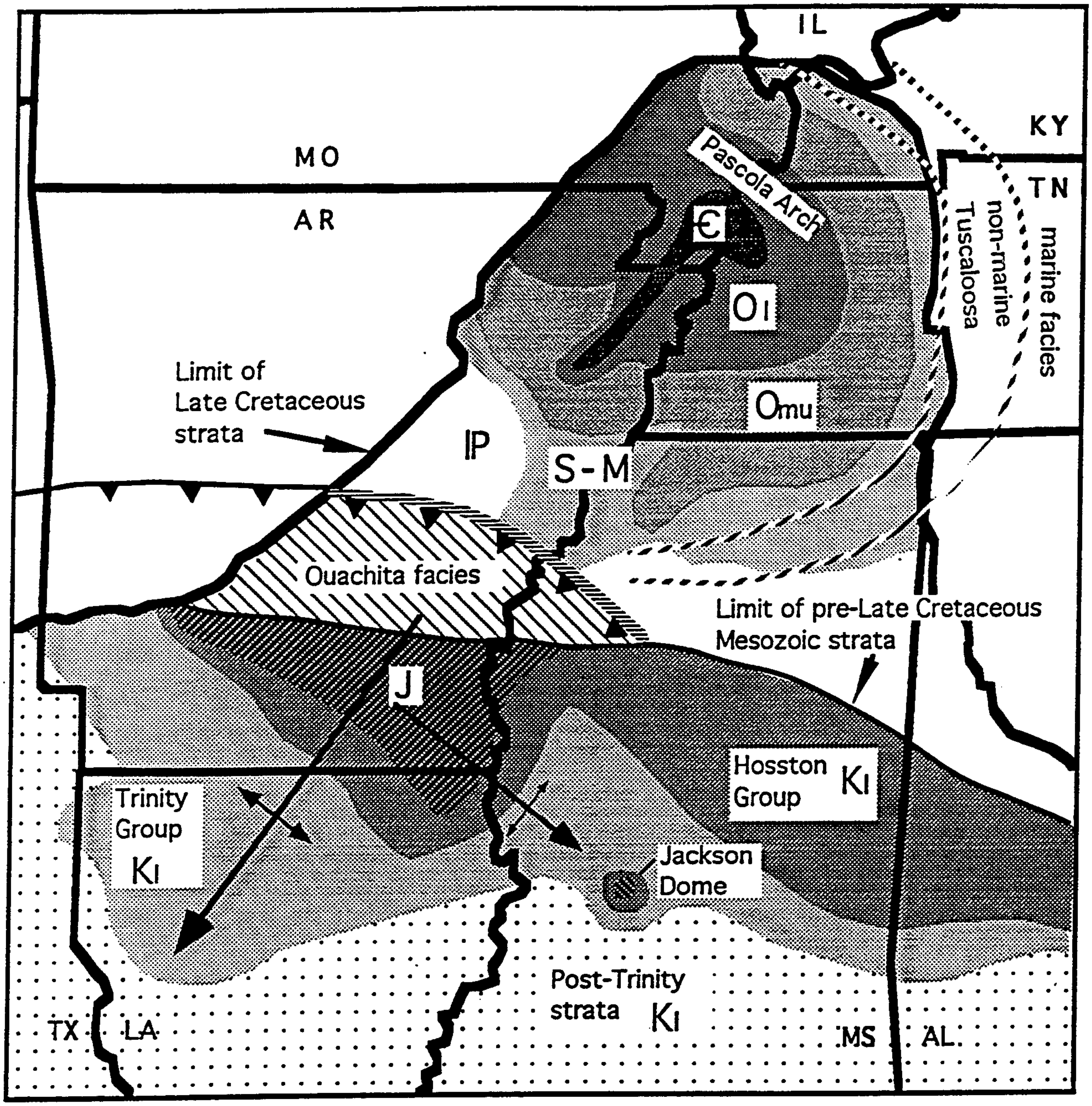


Figure 11. Upper Cretaceous subcrop of the Mississippi Embayment and northern Gulf Coast. Stratigraphic symbols: C = Cambrian, Ol= Lower Ordovician: Omv = Upper and Middle Ordovician; S-M = Silurian, Devonian, Mississippian; IP = Pennsylvanian; J = Jurassic (some Triassic may be included); Kl = Lower Cretaceous. From Cox and Van Arsdale, 1997.

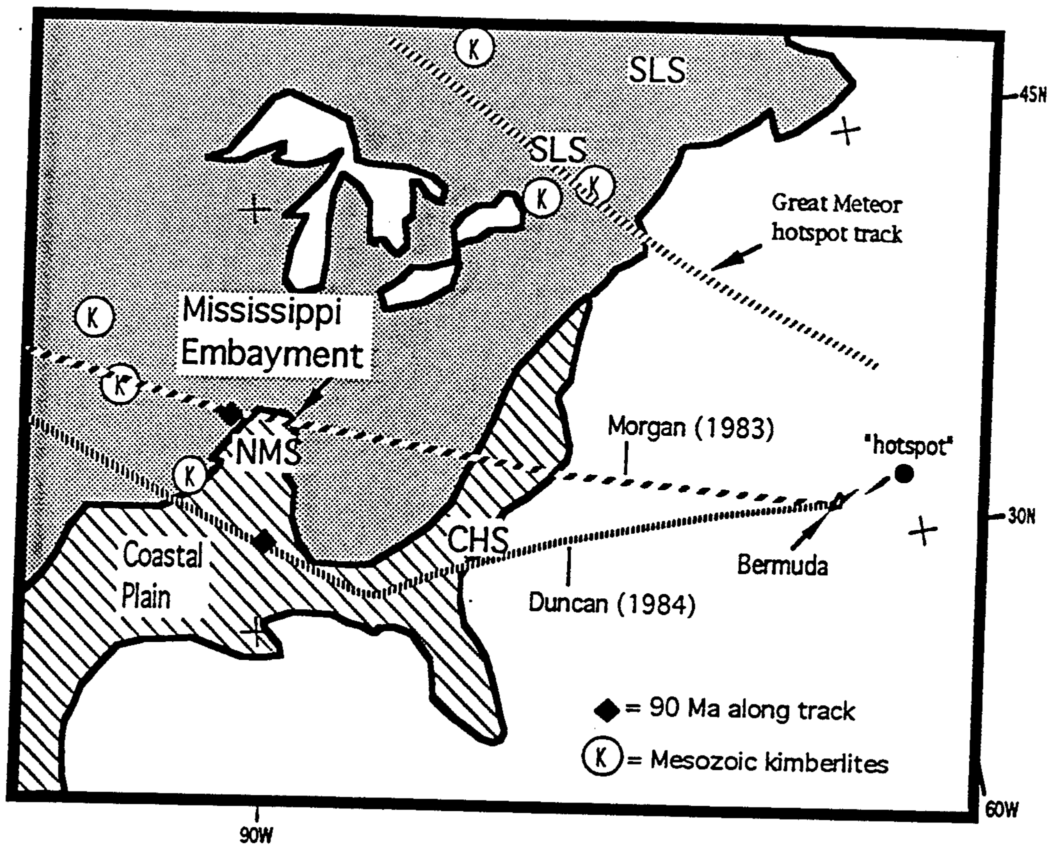


Figure 12. Reconstructed tracks for the Bermuda and Great Meteor hotspot tracks after Morgan (1983) and Duncan (1984). K = Cretaceous kimberlites, NMSZ = New Madrid seismicity; CHS = Charleston seismicity; SLS = St. Lawrence seismicity.

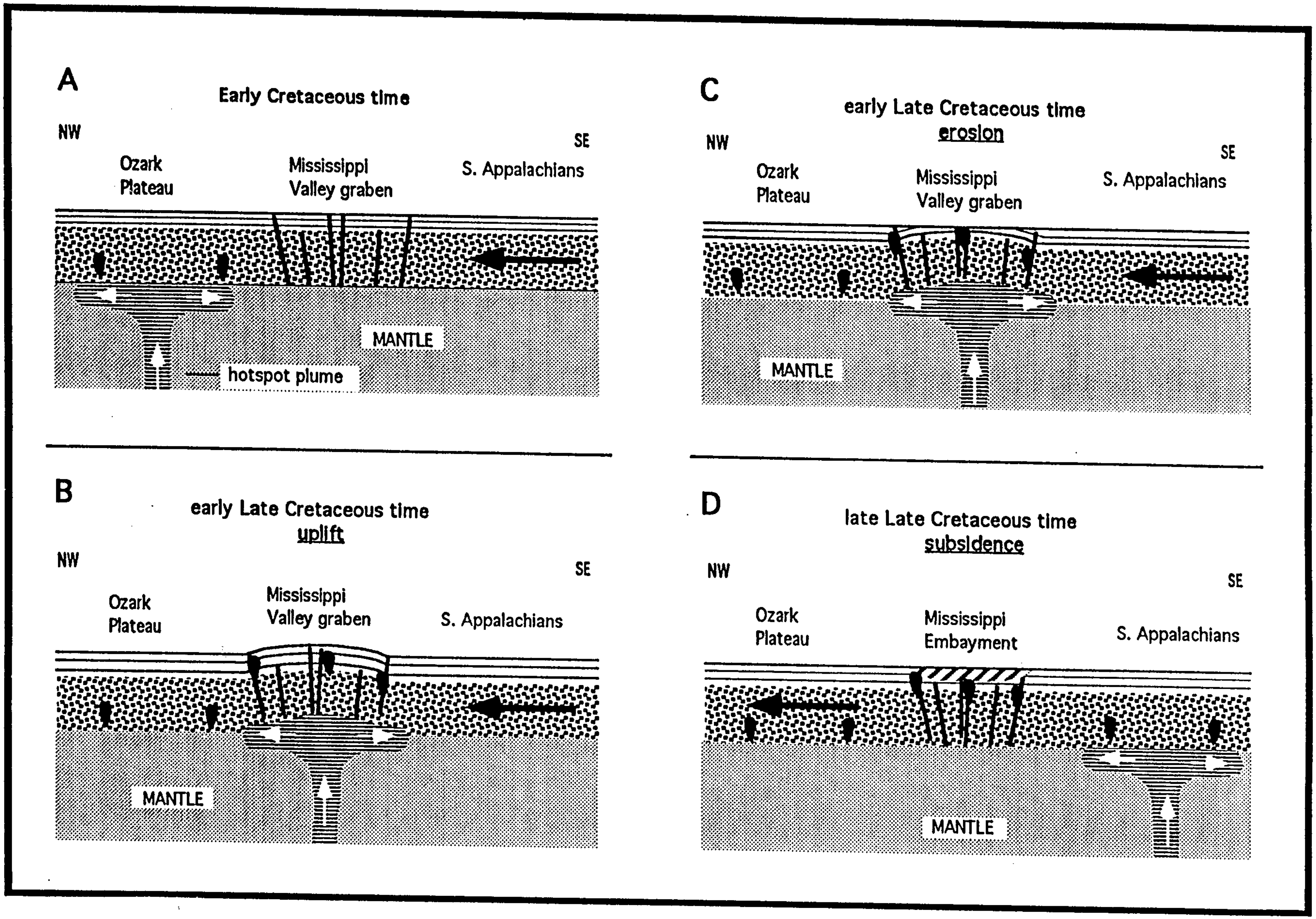


Figure 13. Schematic illustration of passage of the Mississippi embayment region over the Bermuda hotspot during Cretaceous time. From Cox and Van Arsdale, 1997.

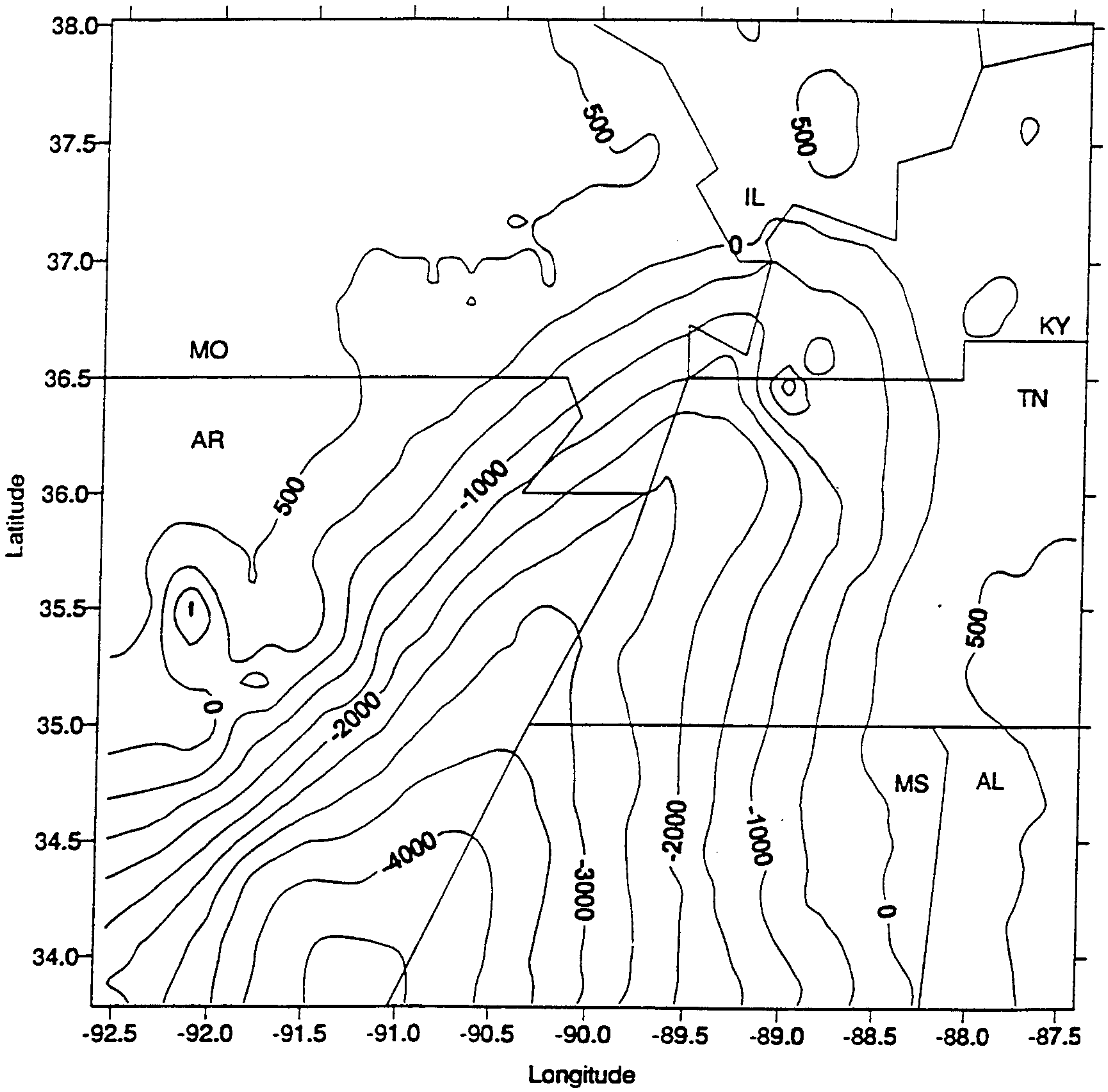


Figure 14. Structure contour map of top of the Paleozoic section. Elevations are in feet. Thickness of the post-Paleozoic section is the positive values of these numbers. From Cox and Van Arsdale, 1997.

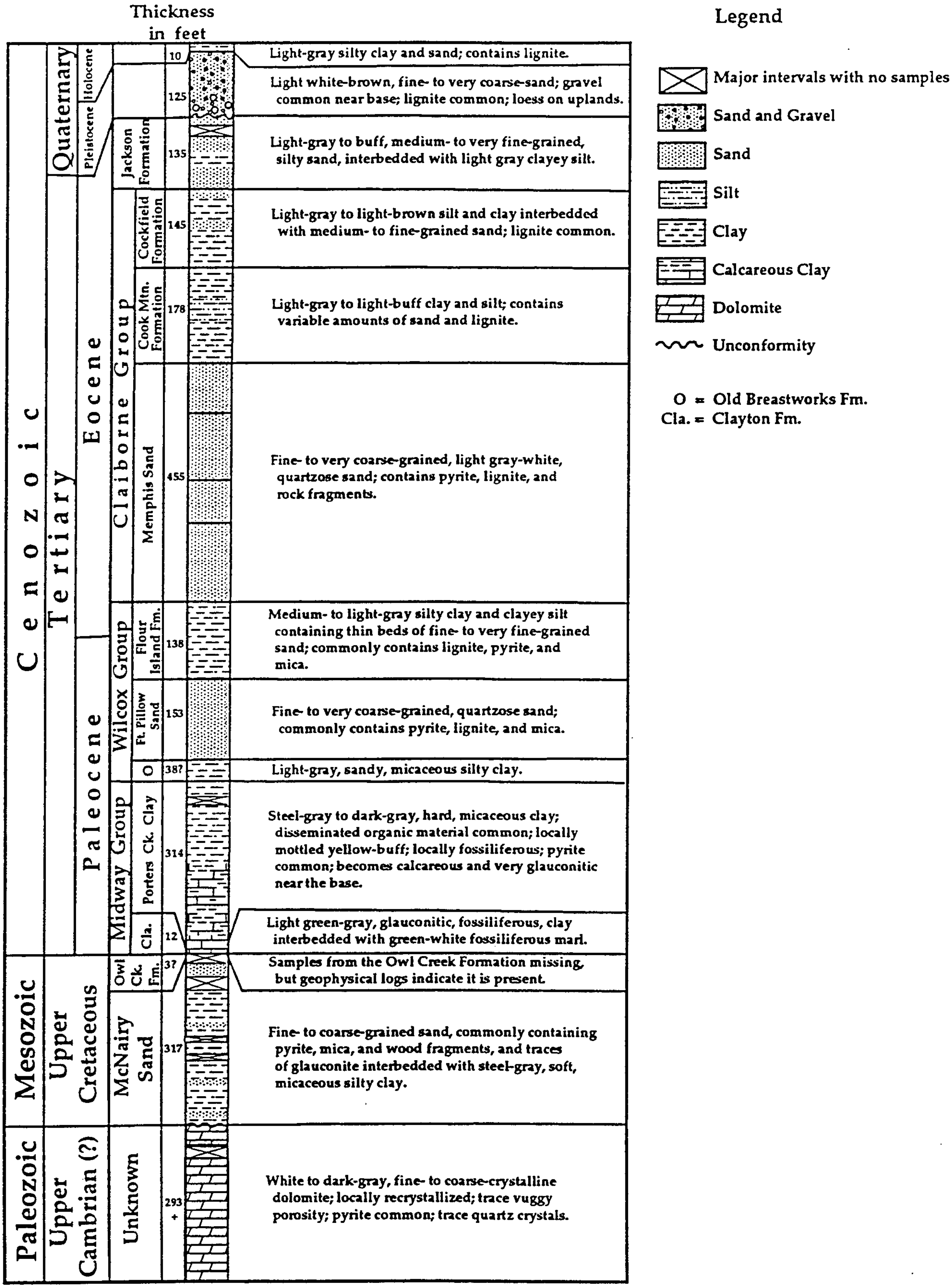


Figure 15. Columnar stratigraphic section of the New Madrid test well X-1. From Purser, 1996.

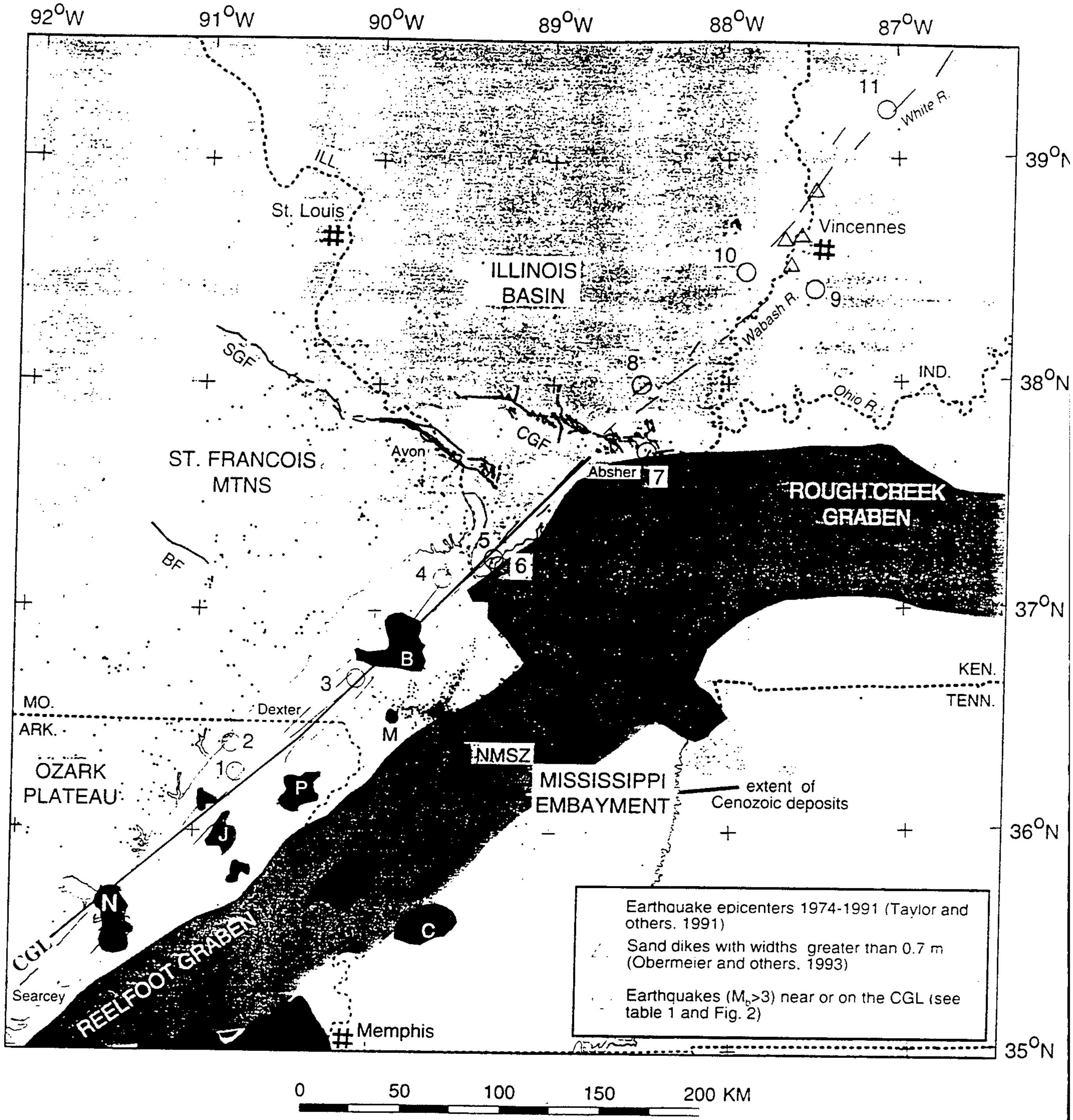


Figure 16. Index map of the Commerce geophysical lineament region. Lightest shaded region denotes region of pre-Cenozoic rocks; medium-shaded denotes region of graben as inferred from aeromagnetic data. Darkest shaded areas are intrusions inferred from gravity data. Thick line from Searcey, Arkansas, to Absher, Illinois, is the Commerce geophysical lineament as seen from shaded-relief aeromagnetic map. Short, parallel and subparallel lines mark northeast-trending edges of aeromagnetic anomalies possibly associated with the Commerce geophysical lineament (CGL). CGF-Cottage Grove fault, SGF-St. Genevieve fault, BF-Black fault, B-Bloomfield, C-Covington, J-Jonesboro, M-Malden, N-Newport, P-Paragould plutons. Numbers identify earthquakes listed in the original source. NMSZ-New Madrid seismic zone. From Langenheim and Hildenbrand, 1997.

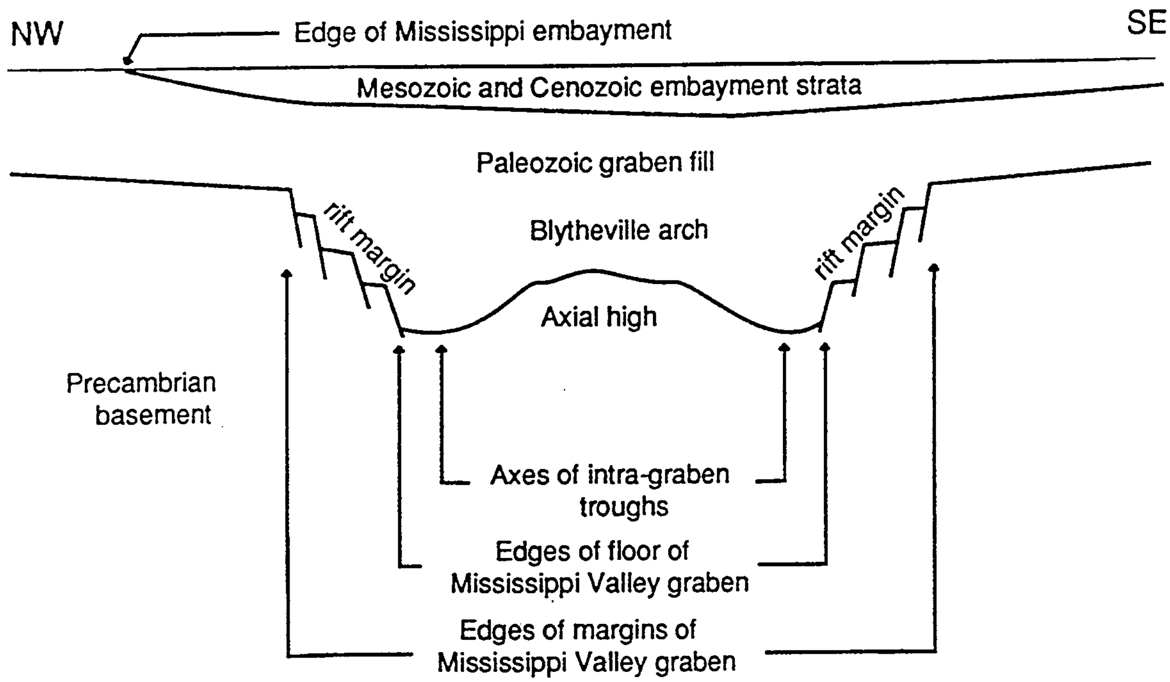


Figure 17. Unscaled and generalized cross section of Mississippi Valley graben. From Wheeler et al., 1994.

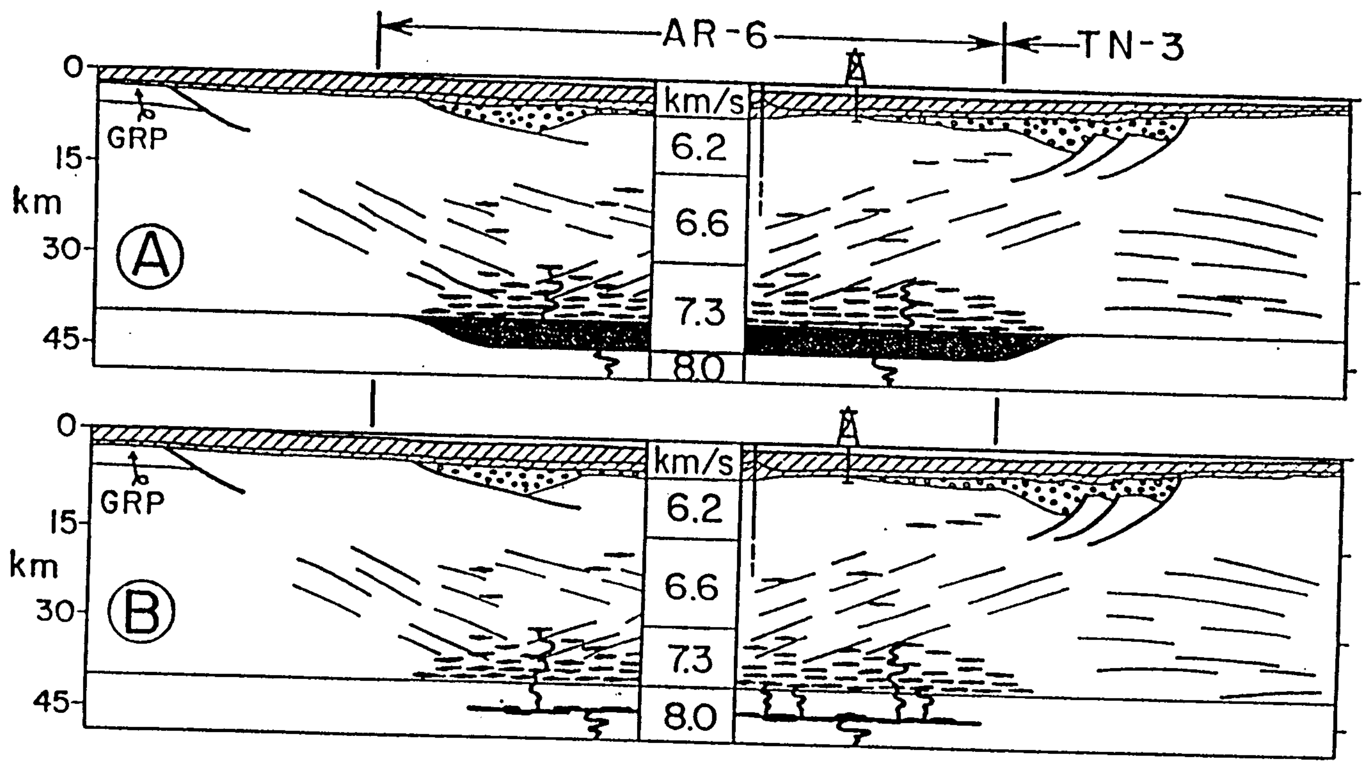


Figure 18. Alternative interpretations of crustal structure beneath the Reelfoot rift. From Nelson and Zhang, 1991.

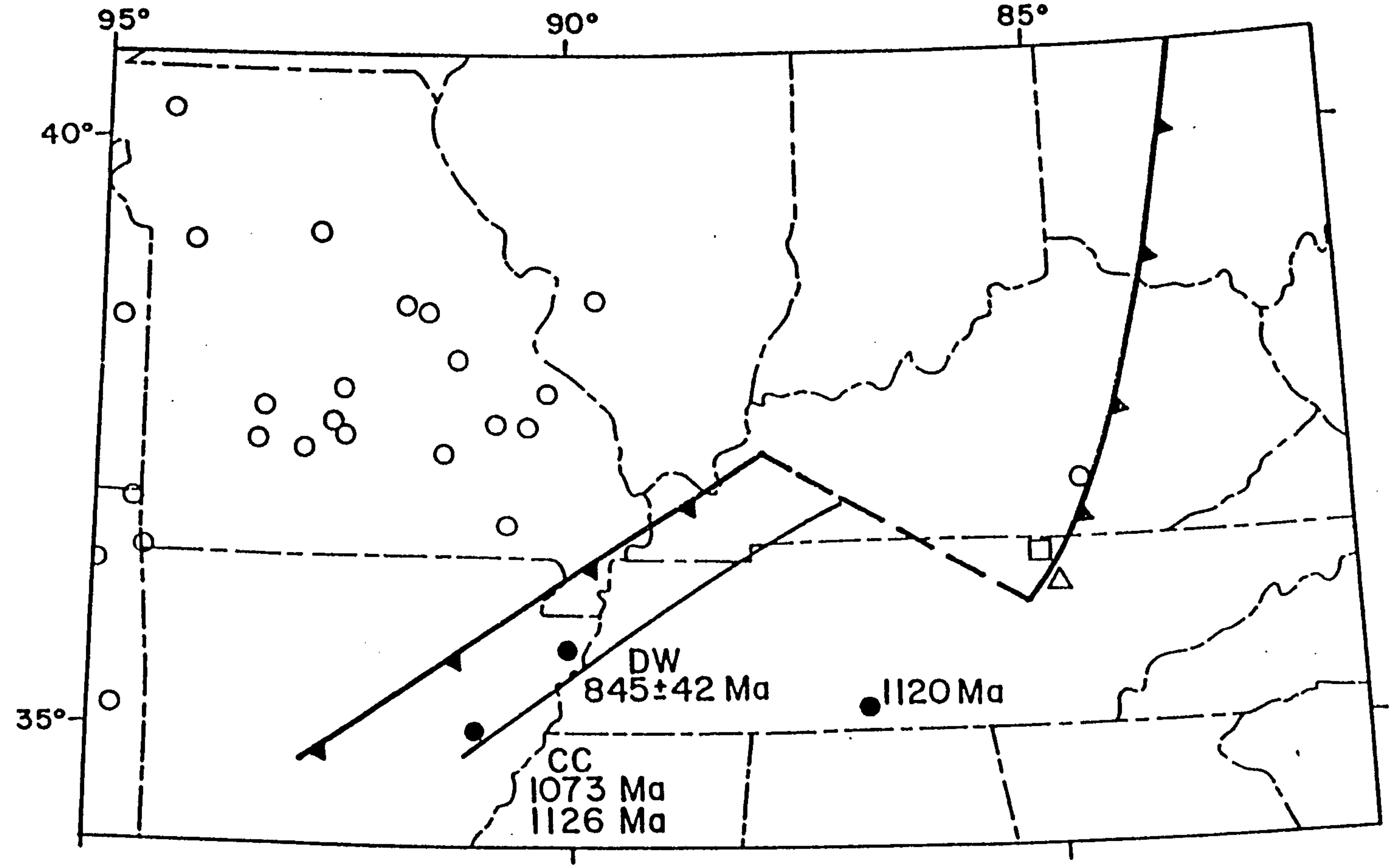


Figure 19. Proposed southern extension of the Grenville Front beneath the Reelfoot rift. Heavy barbed line - Grenville Front. Solid line - east side Reelfoot rift, Dashed line - Rough Creek fault zone. Open circles - wells penetrating unmetamorphosed granites and rhyolites yielding ages of 1.38-1.48 Ga. Solid circles - wells yielding "Grenville-like" basement ages. DW - Dow Wilson well. CC - Cockrell Consolidated No. 1 Carter well. Square - unmetamorphosed silicic volcanic and triangle is granite gneiss defining location of Grenville Front in north-central Tennessee. From Nelson and Zhang, 1991.

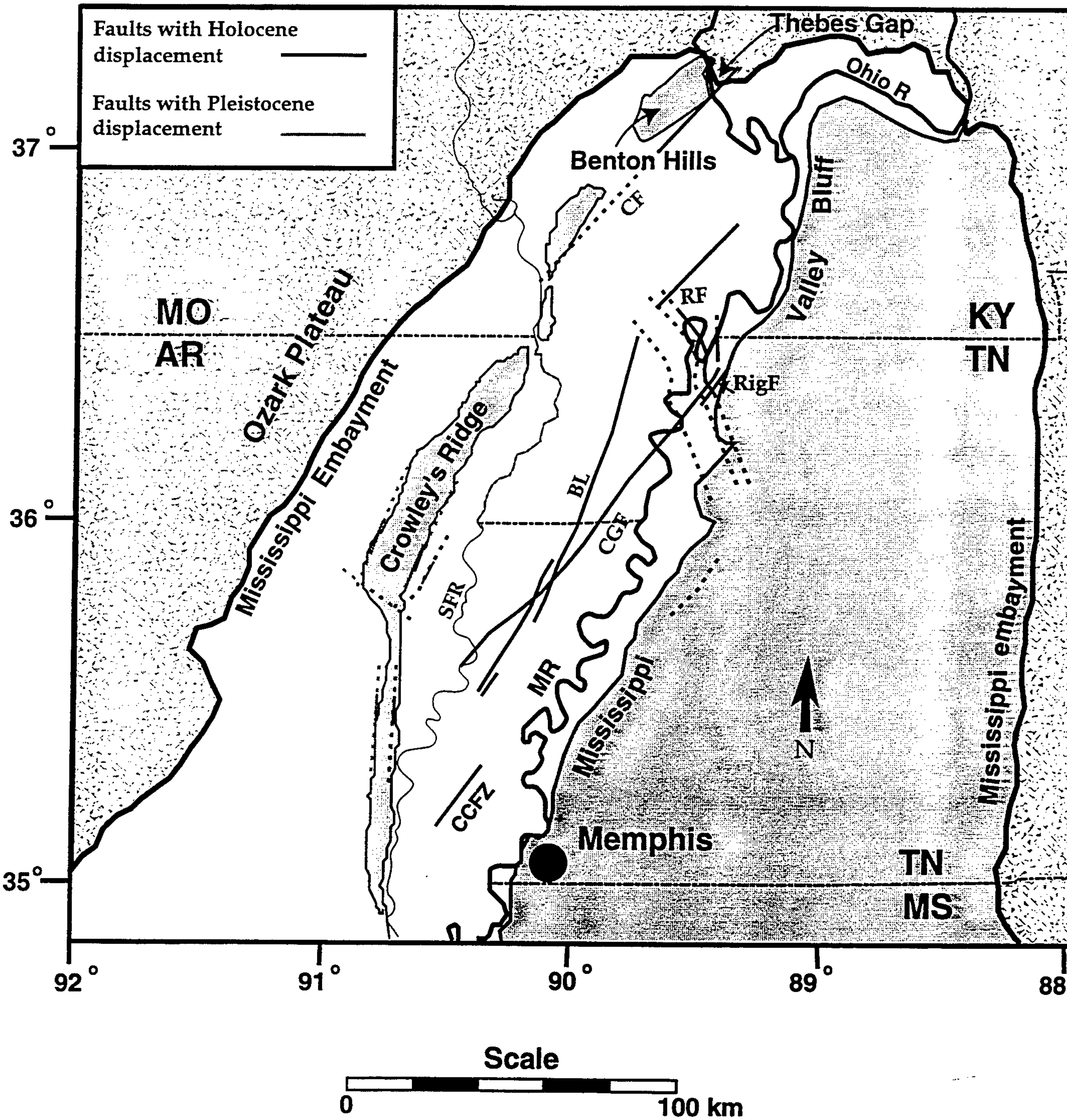


Figure 20. Quaternary fault map of the upper Mississippi embayment. Faults are dotted where displacement is probable. BL=Bootheel lineament, RF=Reelfoot fault, SFR=St. Francis River, MR=Mississippi River, CCRZ=Crittenden County fault zone, CGF=Cottonwood Grove fault, RigF=Ridgely fault, CF=Commerce fault.

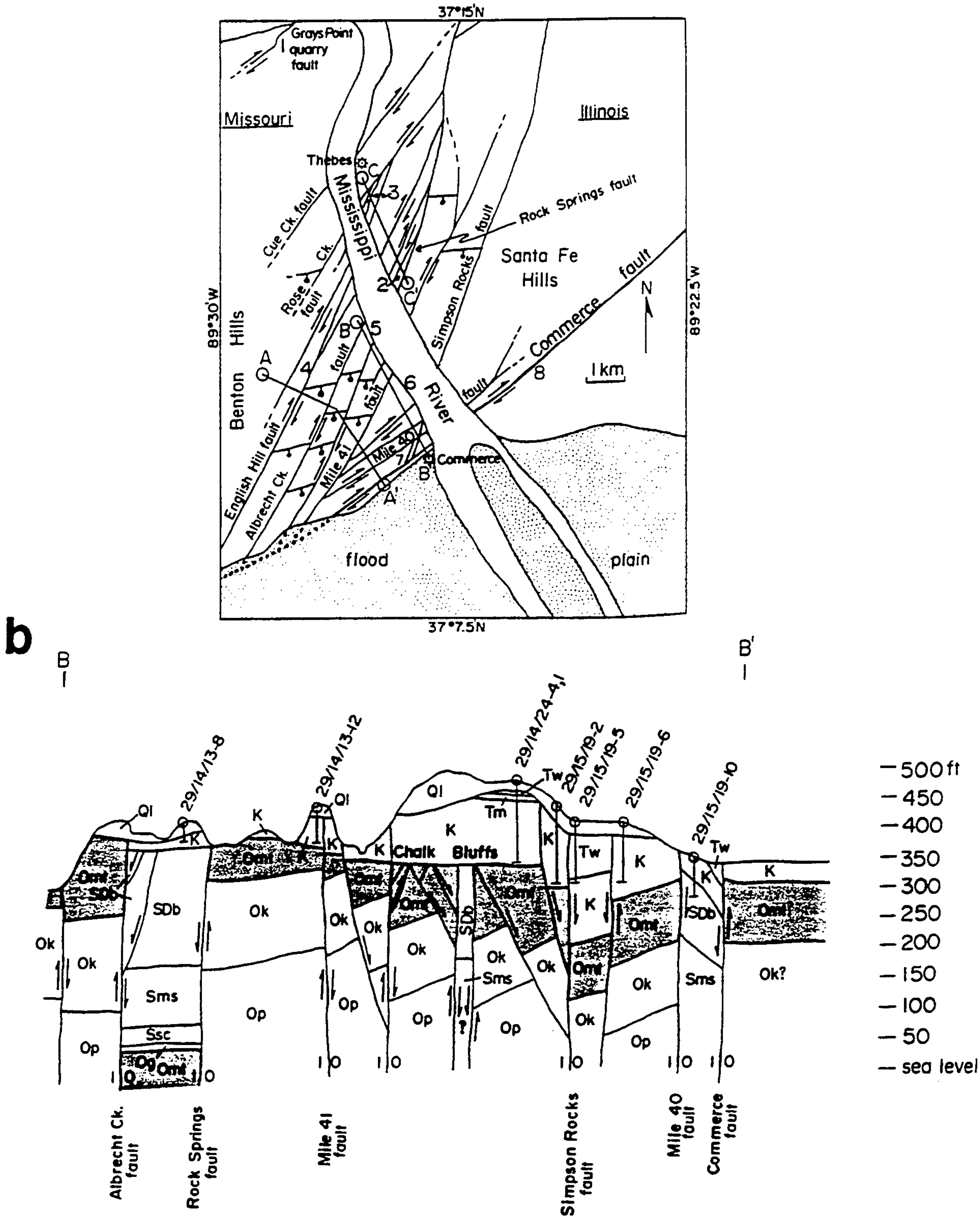


Figure 21. A. Major faults in the Thebes Gap area. Cross sections are labeled A-A', B-B', and C-C'. Arrows indicate the sense of latest movement on Strike-slip faults. Bar-and-ball symbols are on downthrown sides of normal faults.

B. Cross section B-B' with 10 times vertical exaggeration. Unit abbreviations are: Op, Plattin Group; Ok, Kimmswick Limestone; Omt, Thebes Sandstone of the Maquoketa Group; Og, Girardeau Limestone of the Maquoketa Group; Ssc, Sexton Creek Limestone; Sms, Moccasin Springs Formation of the Bainbridge Group; SDb, Bailey Limestone; K, Cretaceous sediments undifferentiated; Tm, Midway Group; Tw, Wilcox Group; Tmg, Mounds Gravel; Ql, Quaternary loess; and Qal, Quaternary alluvium. I and O stand for in and out of page, respectively, and indicate relative horizontal movement across strike-slip faults. From Harrison and Schultz, 1994.

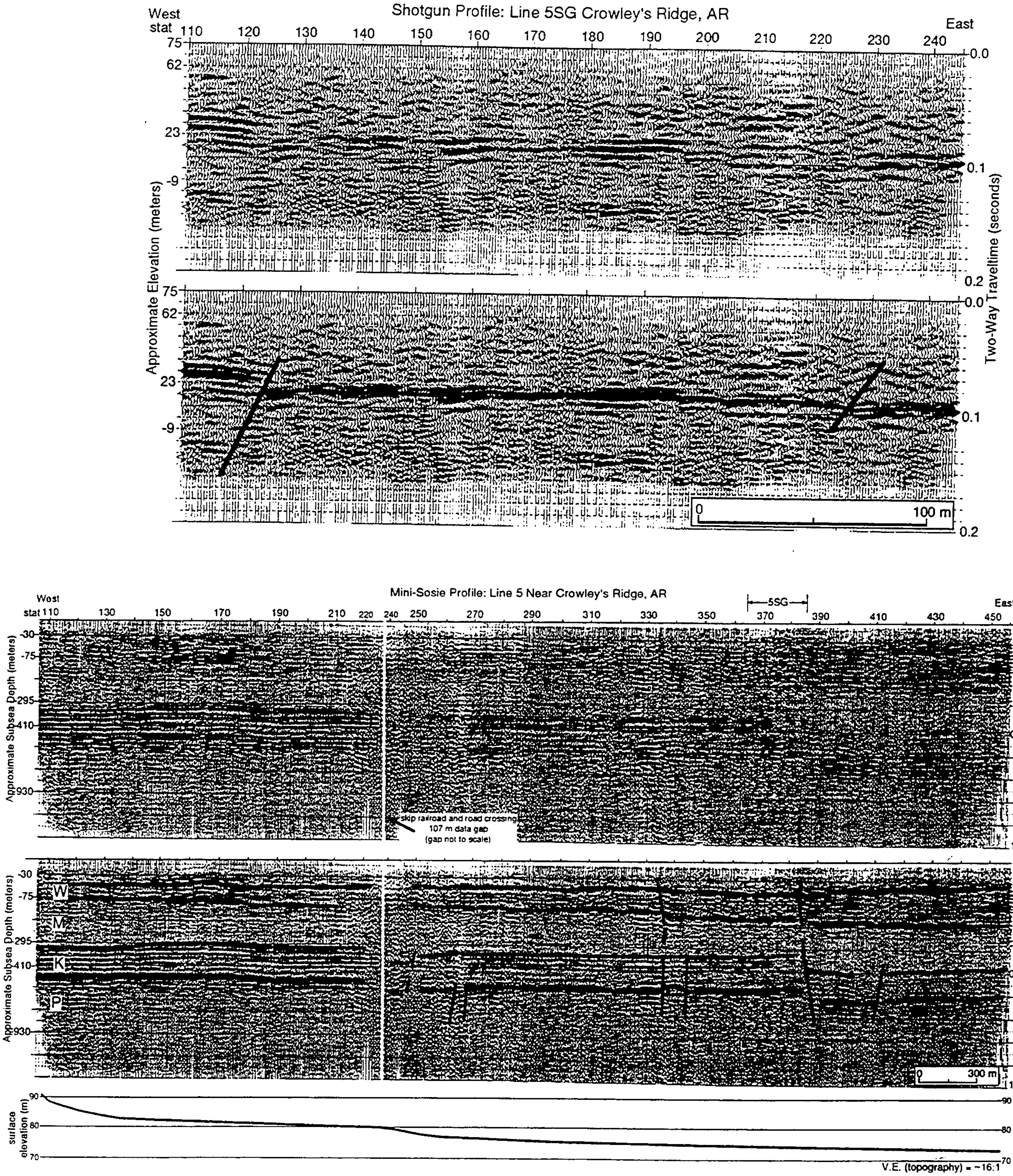


Figure 22. A. Shotgun reflection profile 5SG and geologic interpretation. This line is 329-m long and was shot from STAT 365 to 385 on Mini-Sosie line 5 of part B. The strong reflectors at 0.1 sec are probably gravels at the base of the Pliocene-Pleistocene section.
B. Mini-Sosie reflection line 5 and geologic interpretation. See Figure 24 for location. The line is 5.0-km long. P = Paleozoic, K = Cretaceous, M = Midway Group, and W = Wilcox Group. From Van Arsdale et al., 1995a.

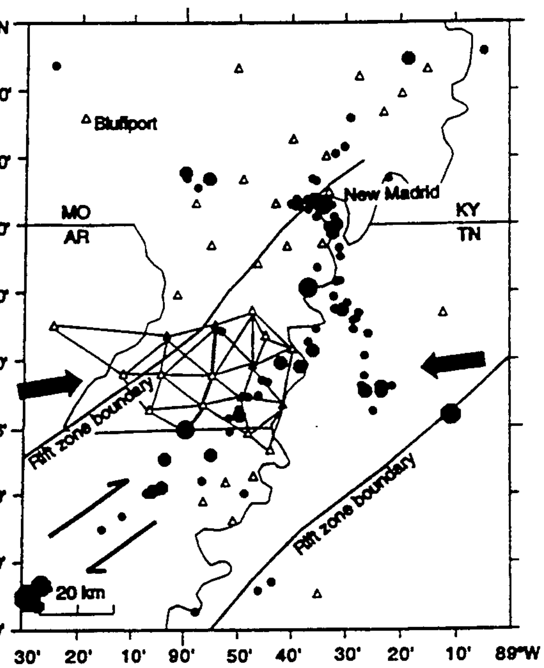


Figure 23. Generalized map of the NMSZ. Well-located earthquake epicenters are shown as a function of size, as are the approximate locations of large (M 8.1 to 8.3) earthquakes of 1811-1812. The boundaries of the reactivated crustal rift zone within which the New Madrid seismicity occurs, termed the Reelfoot rift, are shown as determined from aeromagnetic data. The open triangles indicate triangulation bench marks reoccupied in the 1991 GPS field survey. Those connected by lines indicate the network, chosen for this study, that overlies both the right-lateral strike slip fault zone running down the center of the rift and the northwest rift boundary. Right-lateral strike slip faulting on northeast-tending vertical faults is consistent with east to northeast regional compression. The four solid triangles denote the stations reoccupied by GPS receivers at remote marks, and the thick line divides the eastern and the western subnetworks. From Liu et al., 1992.

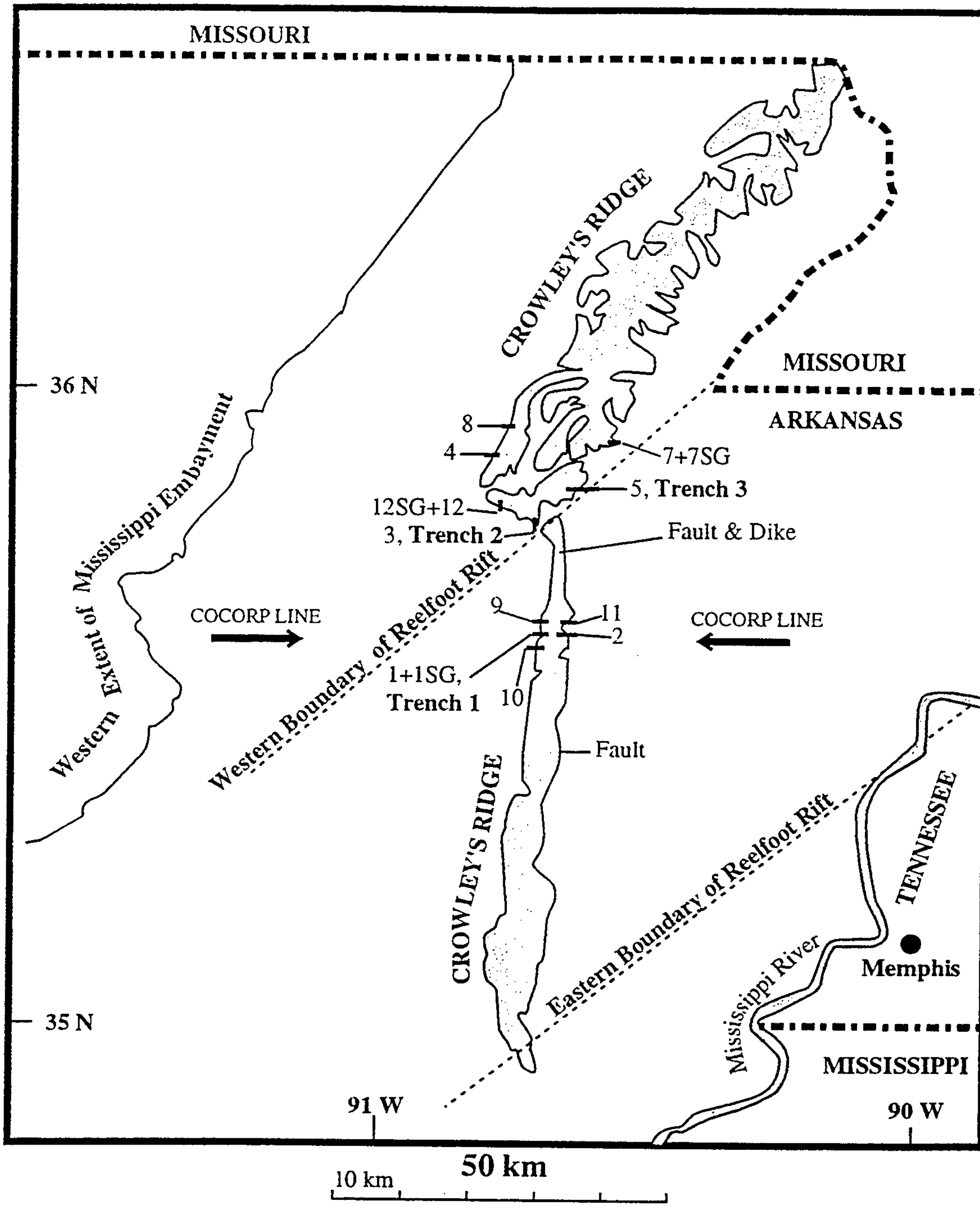


Figure 24. Map of seismic reflection lines and trenches on Crowley's Ridge. Trench 1 is located on shotgun line 1, trench 3 is located 120 m west of Mini-Sosie Line 3, and trench 5 is located 500 m south of shotgun line 5. From Van Arsdale et al., 1995a.

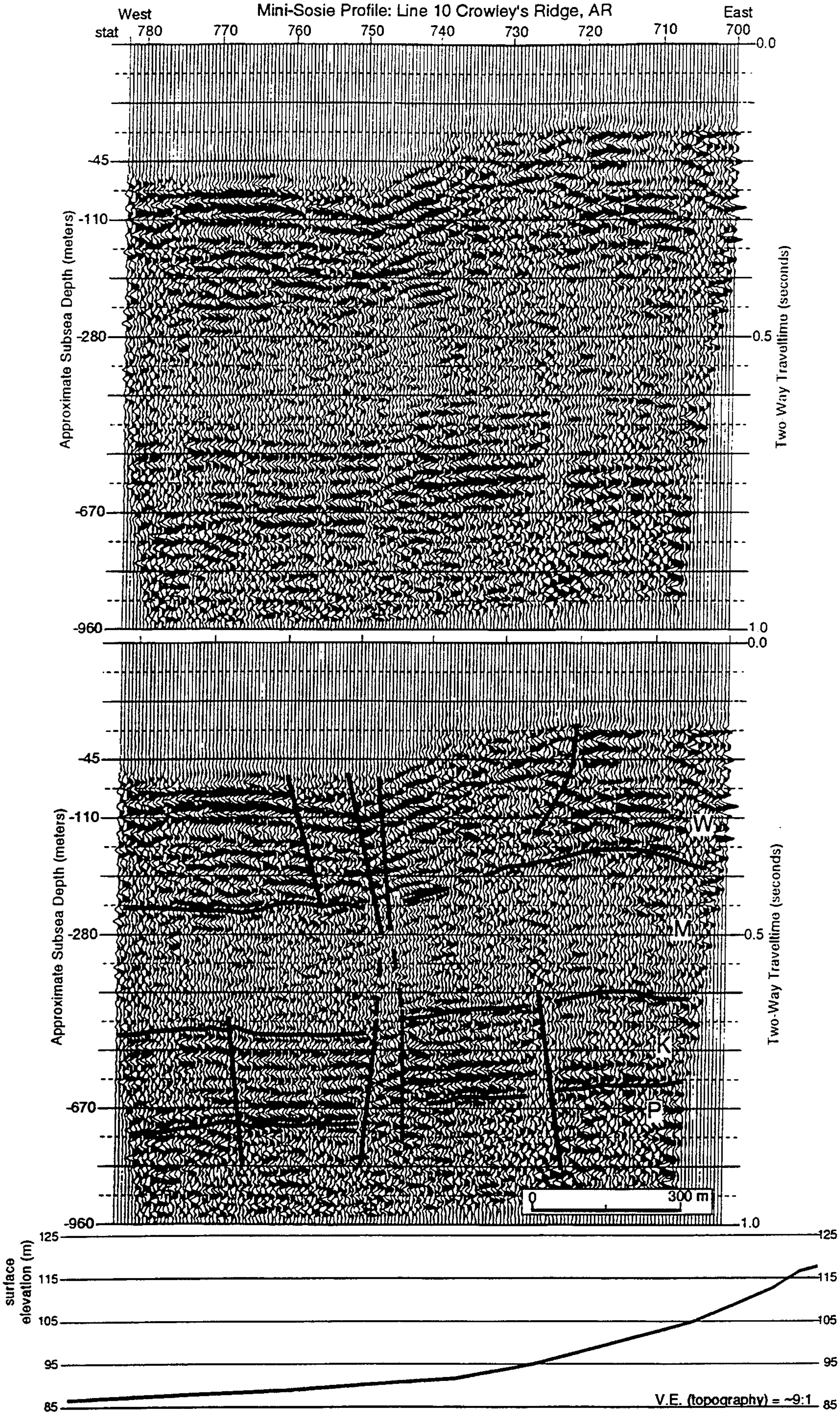


Figure 25. Mini-Sosie reflection line 10 and geologic interpretations. The line is 1.2-km long and is located in Figure 24. P = Paleozoic, K = Cretaceous, M = Midway Group, and W = Wilcox Group. See Figure 24 for location. From Van Arsdale et al., 1995a.

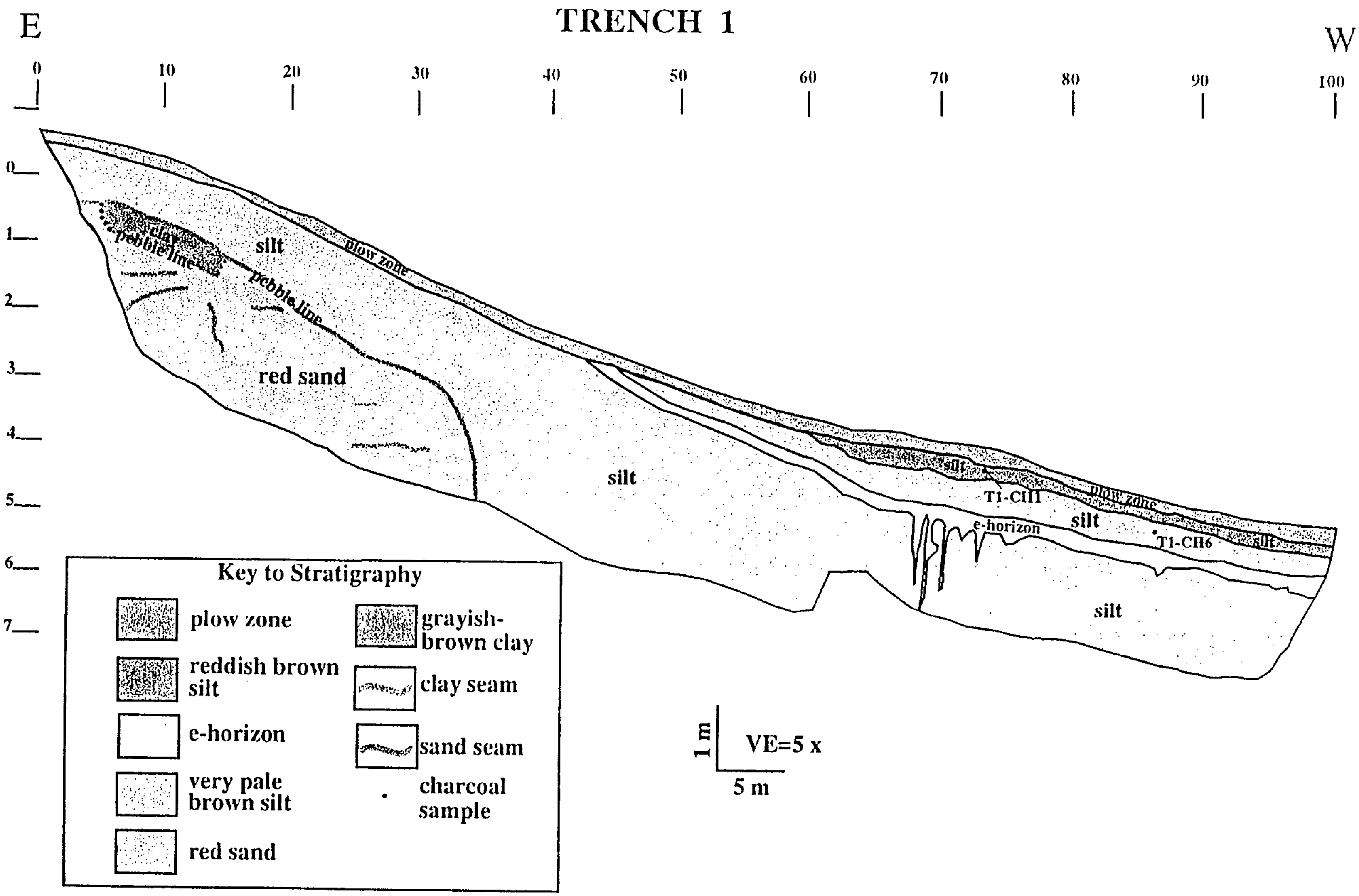


Figure 26. Log of trench 1 of Figure 24. The termination of the sand at 34 m is interpreted to be an erosional contact. The flexure in the e-horizon at 65 m may be tectonic in origin. See Figure 24 for location. From Drouin, 1995.

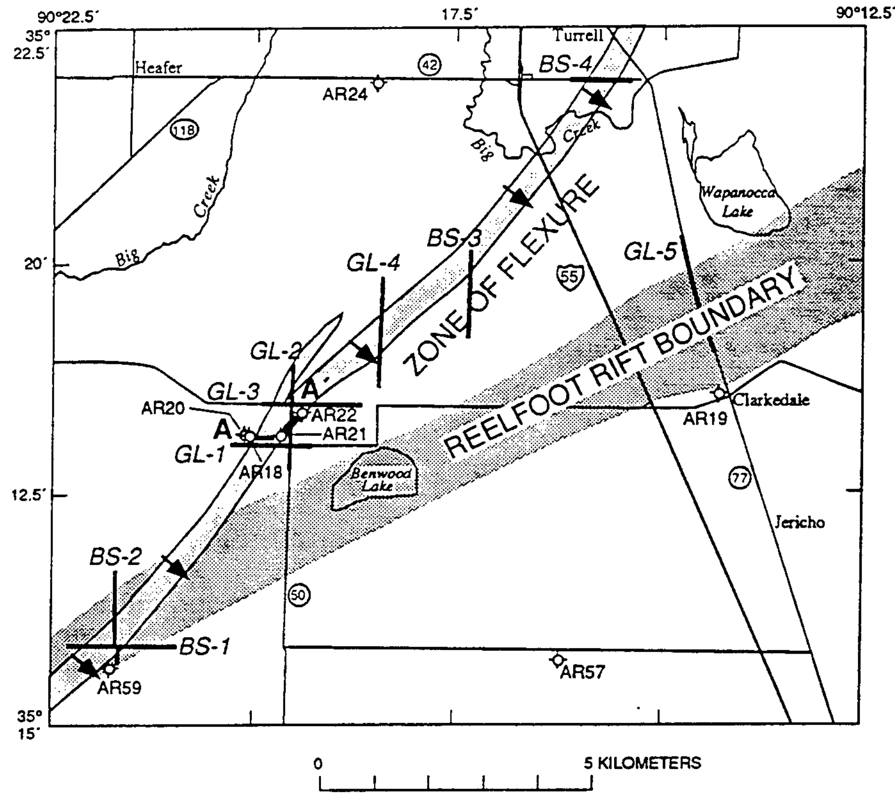


Figure 27. The location of the main zone of flexure in the Wilcox Group overlying the Crittenden County fault zone. The main zone of flexure dips to the southeast, indicating that the faults and flexure are opposite to the down-to-the-northwest normal displacement that marks the southeast boundary of the Reelfoot rift. From Luzietti et al., 1992.

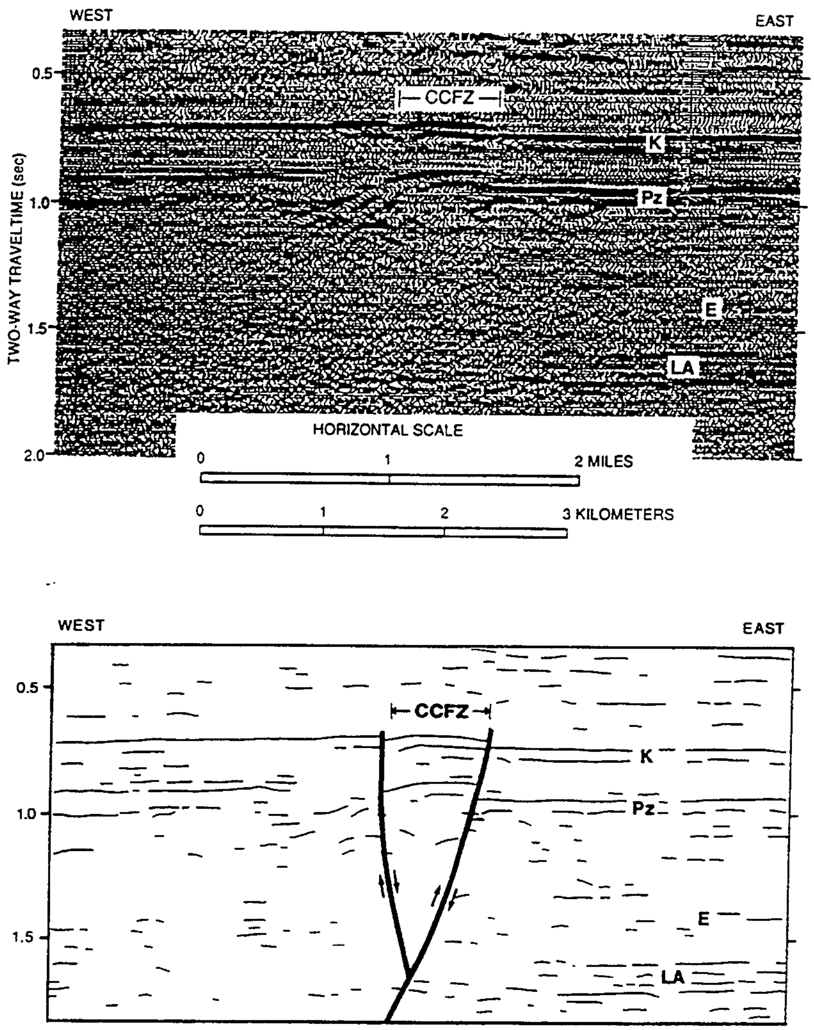


Figure 28. Expression of the Crittenden County fault zone on seismic reflection profiles: showing well-defined reverse fault and companion normal fault, both of which accommodate all of the displacement. Inferred faults are shown by solid bold lines; arrows show relative direction of vertical slip. Labeled reflectors are: K-top of Cretaceous, Pz-top of Paleozoic, E-top of Elvins Group, LA-top of lithic arenite. From Crone, 1992.

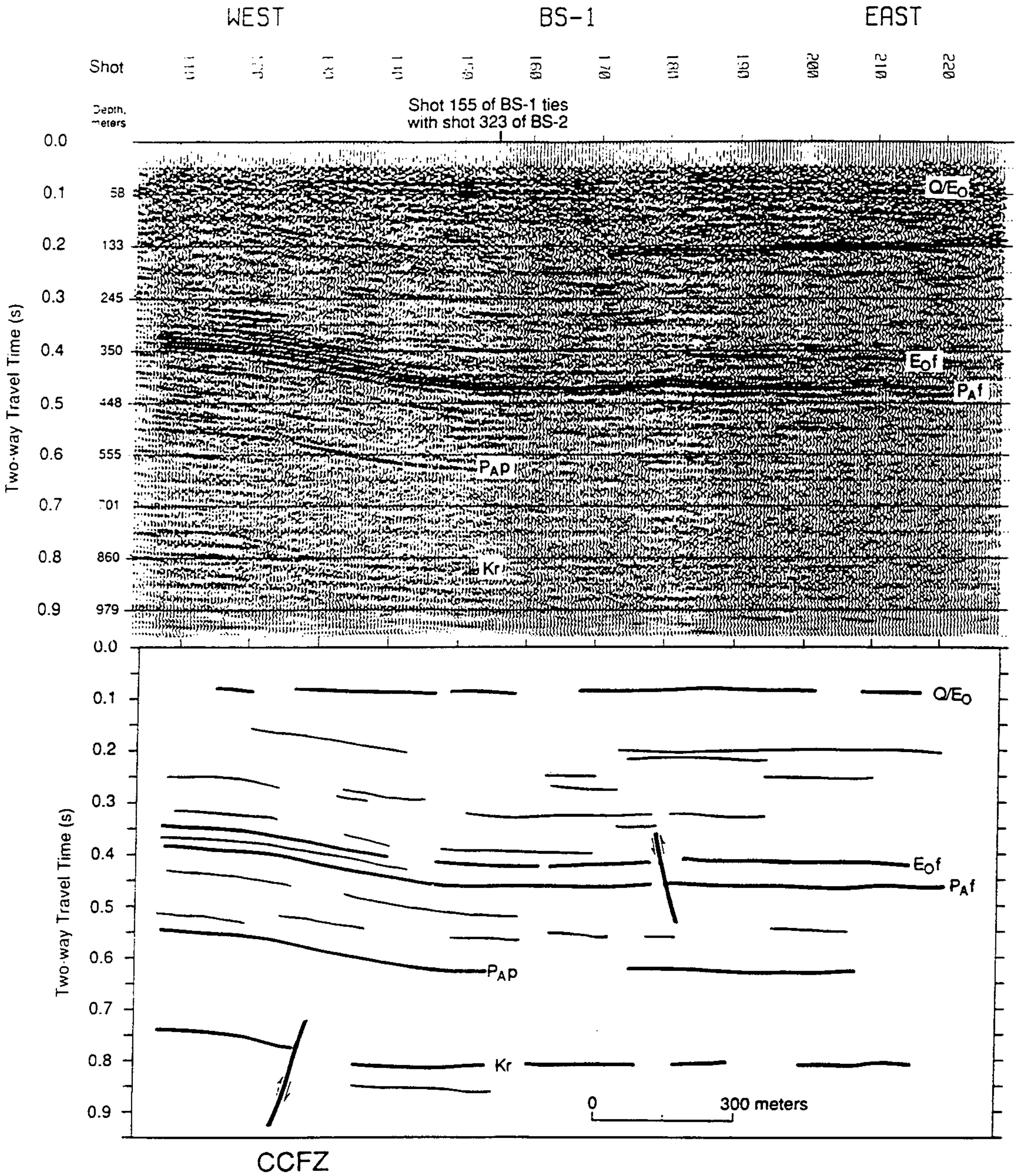


Figure 29. Migrated seismic-reflection profile BS-1 and line drawing. Q/E_o=Quaternary/Eocene unconformity boundary; E_of=Eocene Flour Island Formation; P_Af=Paleocene Fort Pillow Sand; P_Ap=Paleocene Porters Creek Clay; Kr=Cretaceous rocks. The CCFZ is shown by reverse fault below shot point 130. Notice the onlapping and high-amplitude reflectors between 0.10 and 0.25 s, suggesting that thinning of the geologic section occurred in the middle to late Eocene. See Figure 27 for location. From Luzietti et al., 1992.

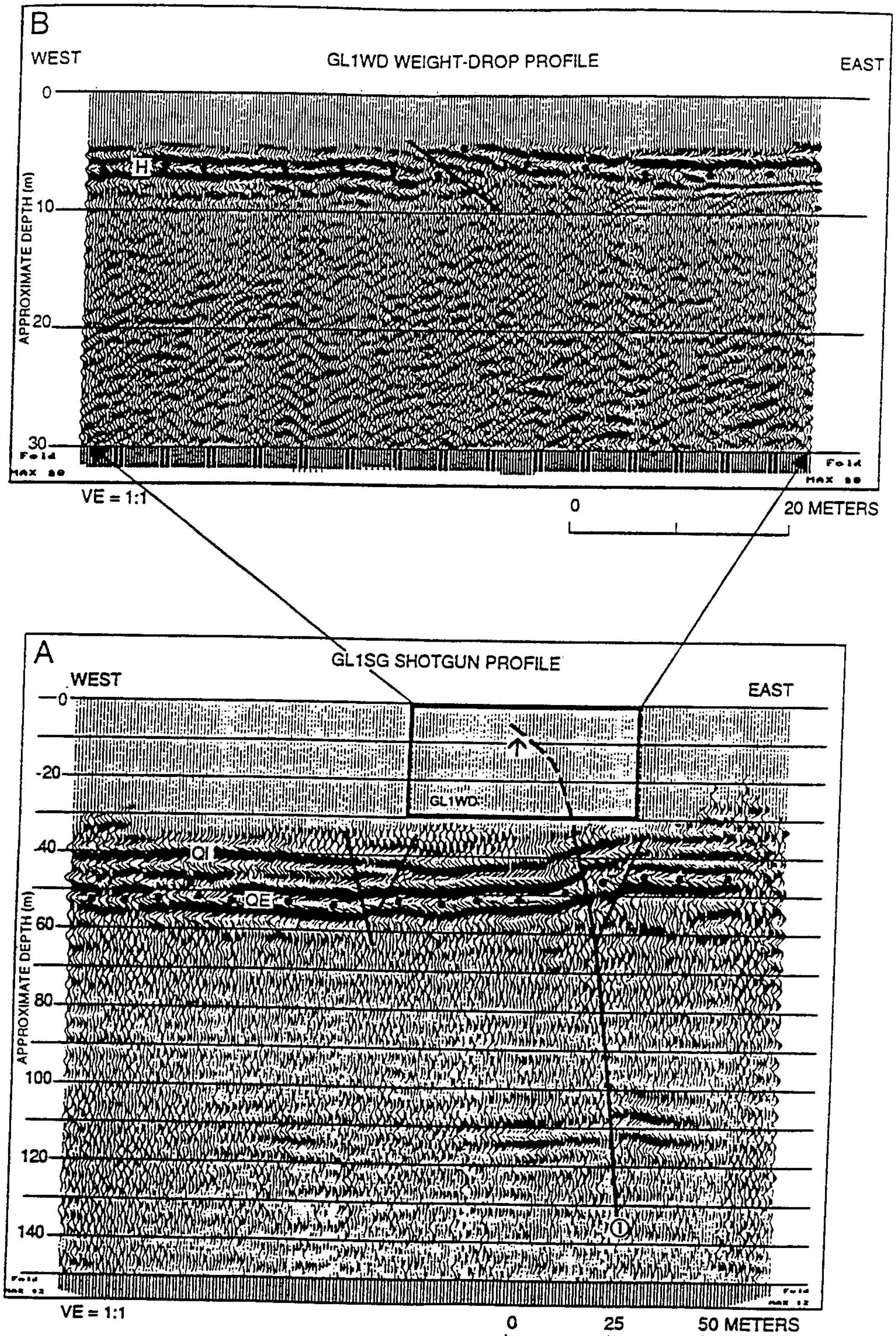


Figure 30. A. Shotgun-source seismic reflection profile GL1SG (depth section). Two reverse faults (heavy lines) are inferred to cut the QE boundary (dotted horizon) and overlying lower Quaternary (Q1) deposits. Inset box shows depth and lateral extent of weight-drop seismic-reflection data. See Figure 27 for location.

B. Weight-drop seismic reflection profile GL1WD (depth section) outlined in figure A. Fault (heavy line) appears to displace H reflector (dotted) over itself east-to-west. From Williams et al., 1995.

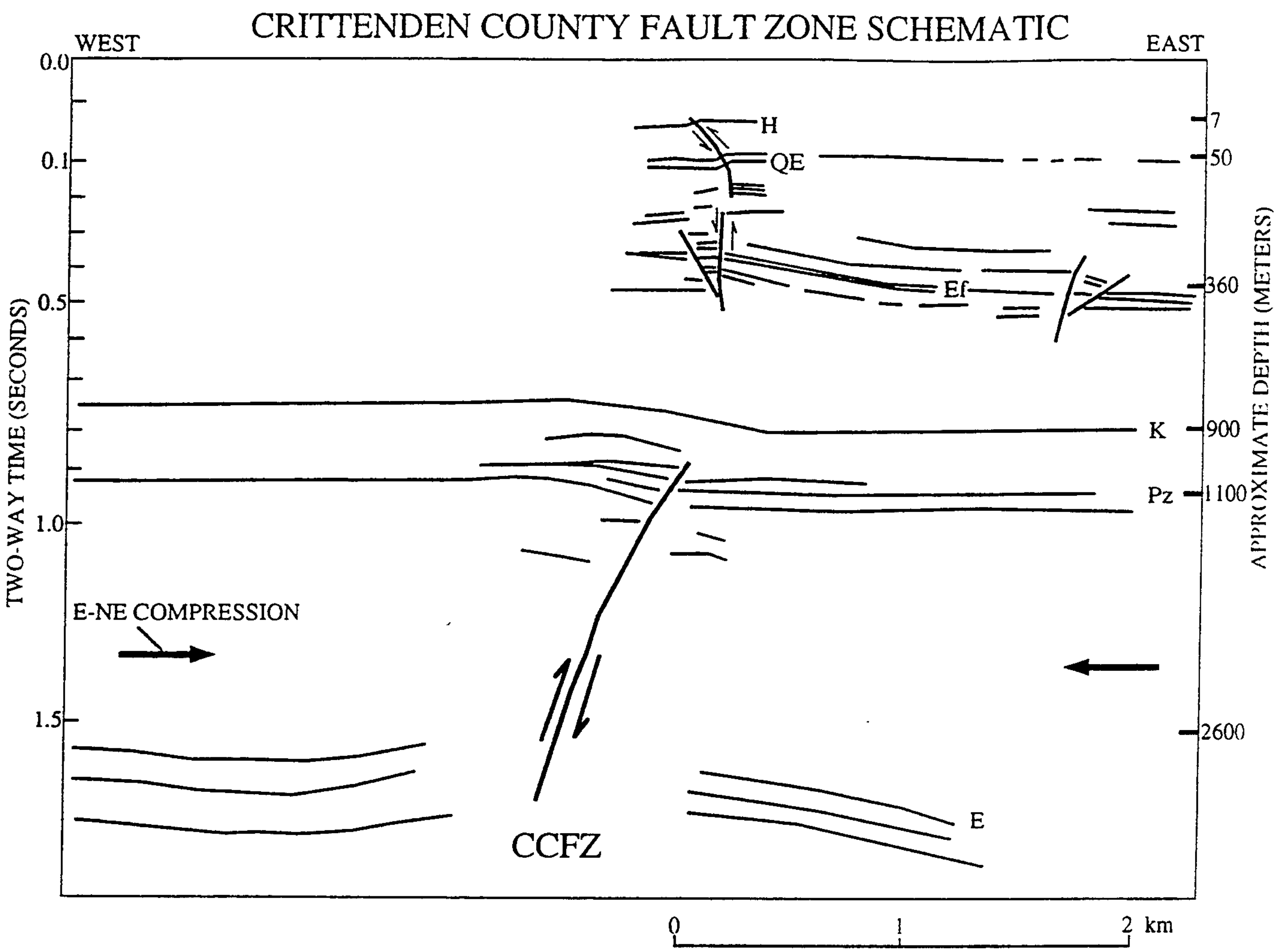


Figure 31. East-west schematic representation of faulting interpreted from seismic reflection data across the CCFZ at location of seismic reflection profile GL1. Faults are indicated by heavy lines and reflections, identified in seismic reflection data, are shown with light lines and previously assigned names. Regional east-northeast compressive stress shown by large arrows. From Williams et al., 1995.

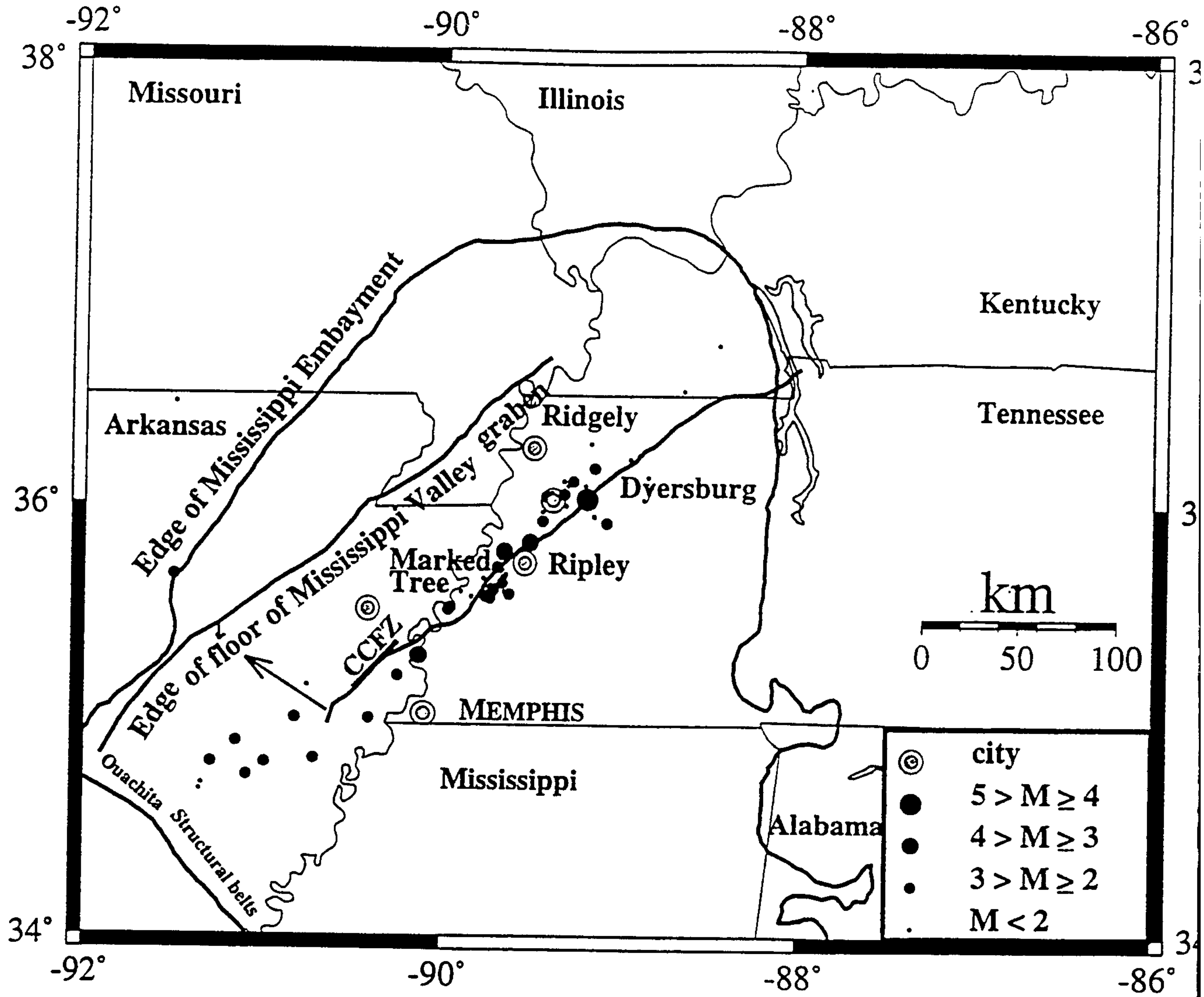


Figure 32. Seismicity along the eastern margin of the Reelfoot rift from 1974 to 1994. From Chiu et al., in press.

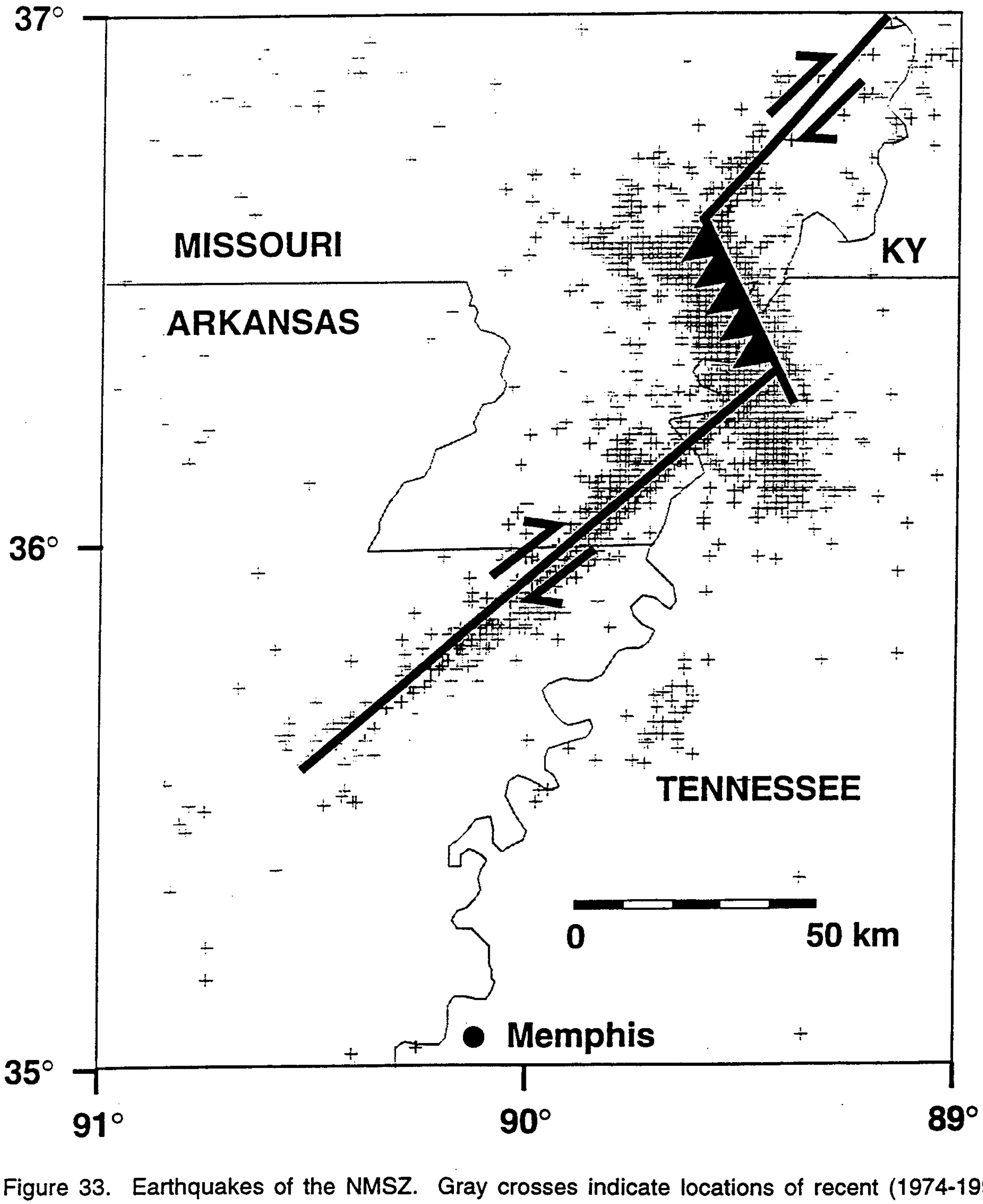


Figure 33. Earthquakes of the NMSZ. Gray crosses indicate locations of recent (1974-1991) seismicity. Bold lines show simple tectonic model of the seismic zone as a left-stepping, right-lateral strike-slip fault zone. From Schweig and Van Arsdale, 1996.

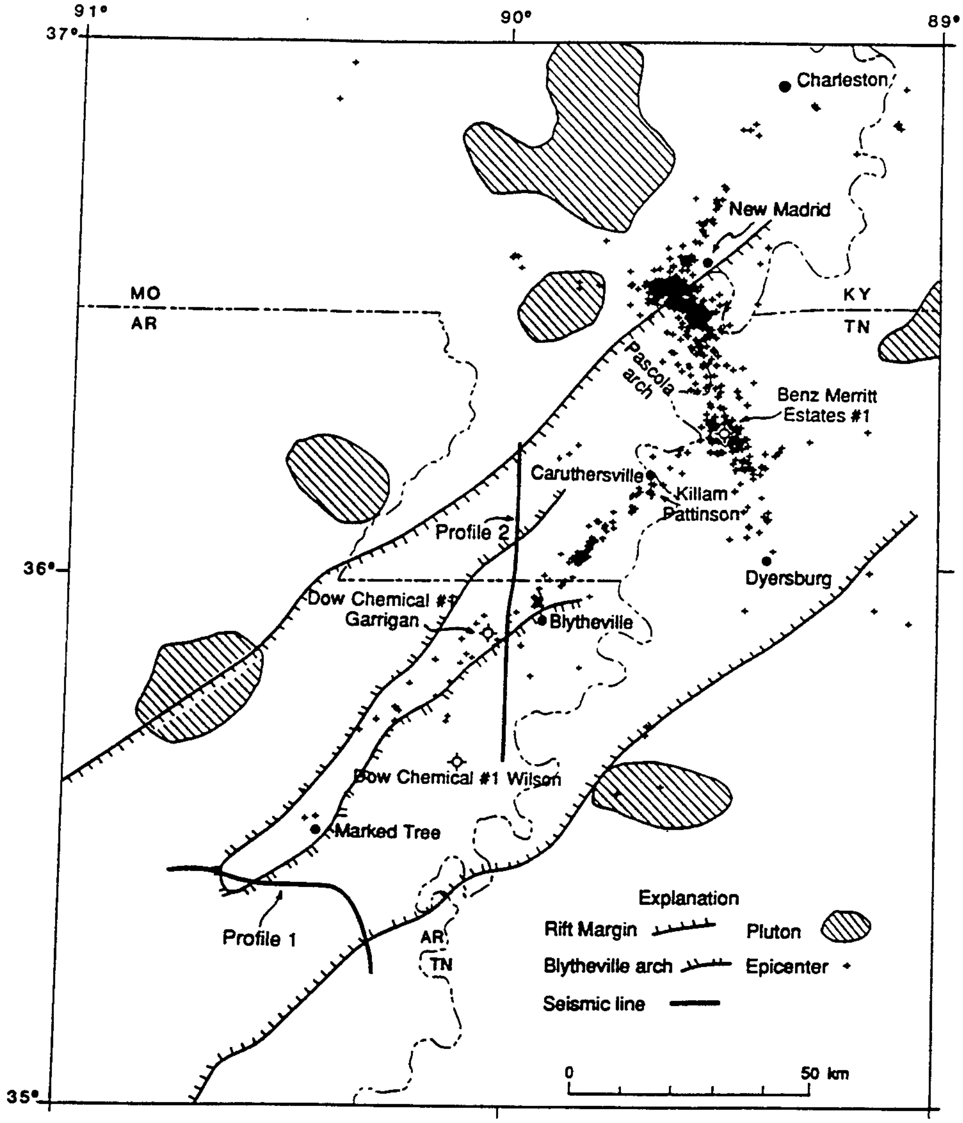


Figure 34. Index map of New Madrid seismic zone showing epicenters, rift boundaries and plutons, Blytheville arch, general location of Pascola arch, seismic reflection profile lines 1 and 2, and selected drill holes. From McKeown et al., 1990.

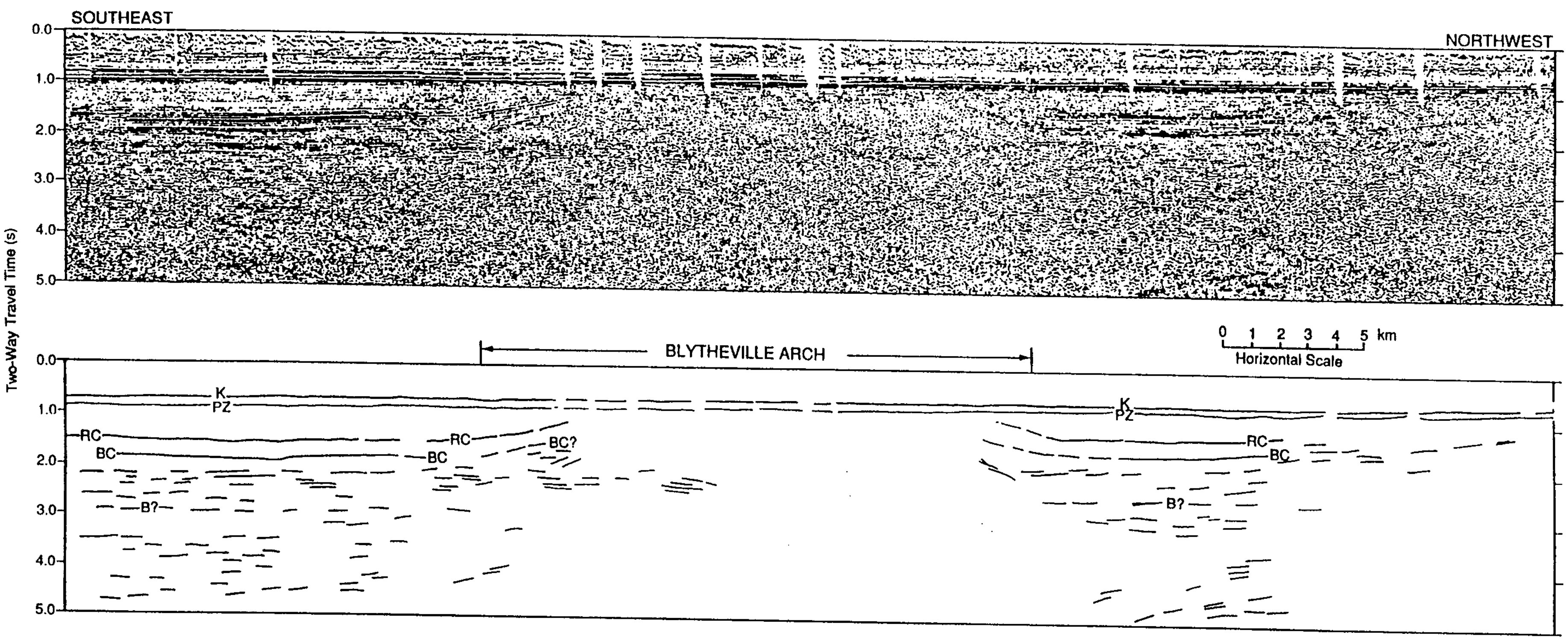


Figure 35. Coherency-filtered north-south seismic reflection record section of line P2 and line drawing processed to intersect Blytheville arch at about 90°. K=Tertiary-Upper Cretaceous contact; Pz=Upper Cretaceous-Paleozoic contact; RC=top of red clay unit; BC=top of basal clastic rock unit; B=Paleozoic crystalline rock contact. See Figure 34 for location. From McKeown et al., 1990.

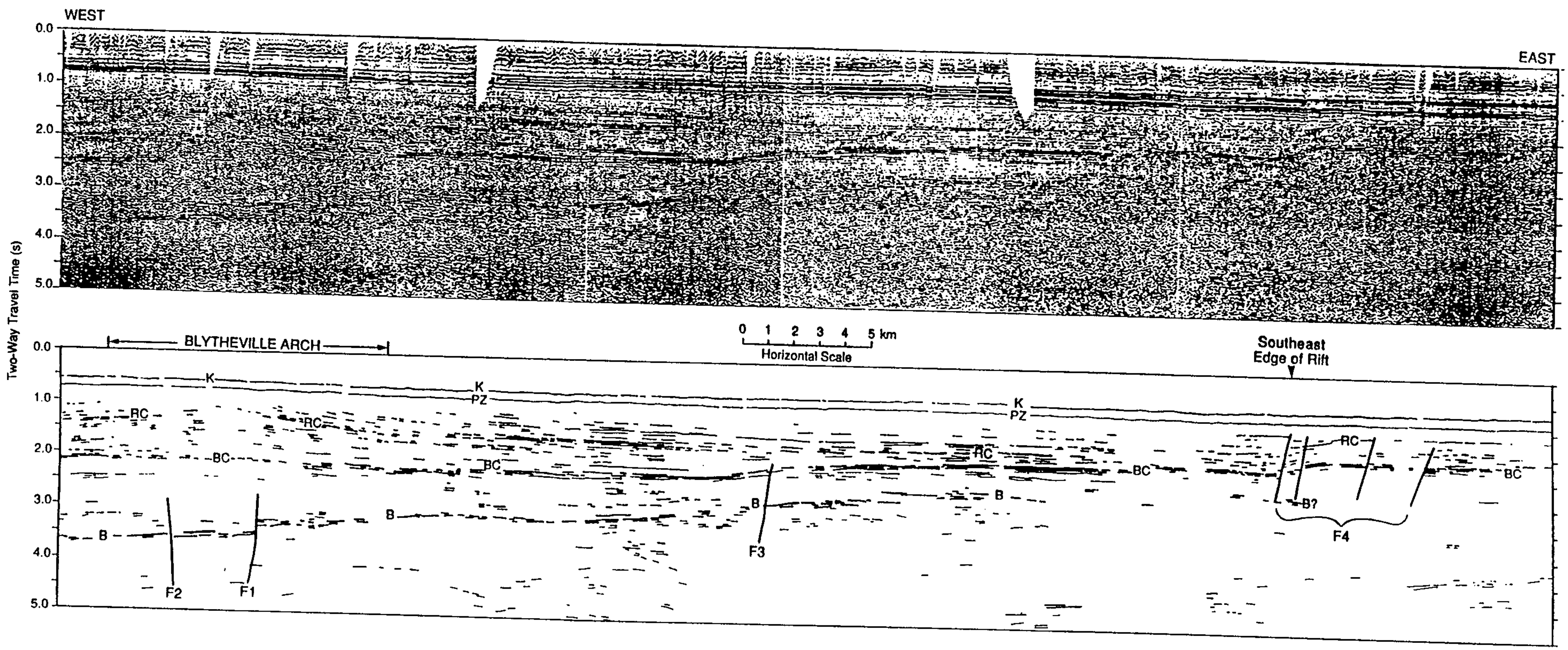


Figure 36. Coherency-filtered seismic reflection record section of line P1 and line drawing extending from southeast boundary of Reelfoot rift northwestward across southwest end of Blytheville arch. K=Tertiary-Upper Cretaceous contact; Pz=Upper Cretaceous-Paleozoic contact; RC=top of red clay unit; BC=top of basal clastic rock unit; B=Paleozoic-crystalline rock contact. See Figure 34 for location. From McKeown et al., 1990.

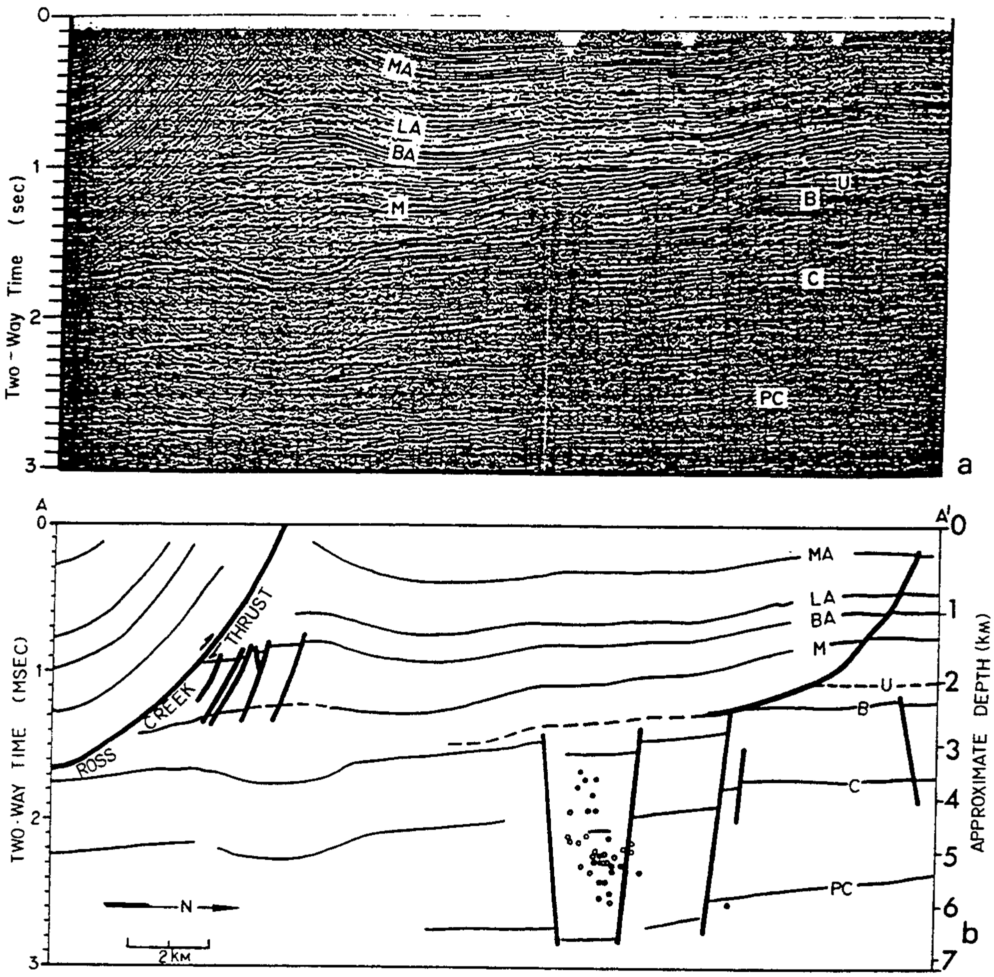


Figure 37. Reflection seismic section A-A' and interpretation. Location of the seismic section is perpendicular to the E-W oriented Paleozoic graben and passes through the center of the central Arkansas seismic swarm. Open circles represent U.S.G.S. data from 1982; closed circles, Portable Array for Numerical Data Acquisition (PANDA) data from 1987. Reflectors: MA=middle Atoka; LA=lower Atoka; BA=Basal Atoka; M=Morrowan; U=pre-Morrowan unconformity; B=Boone Formation; C=top of Cambrian clastics; PC=Precambrian reflector. From Schweig et al., 1991.

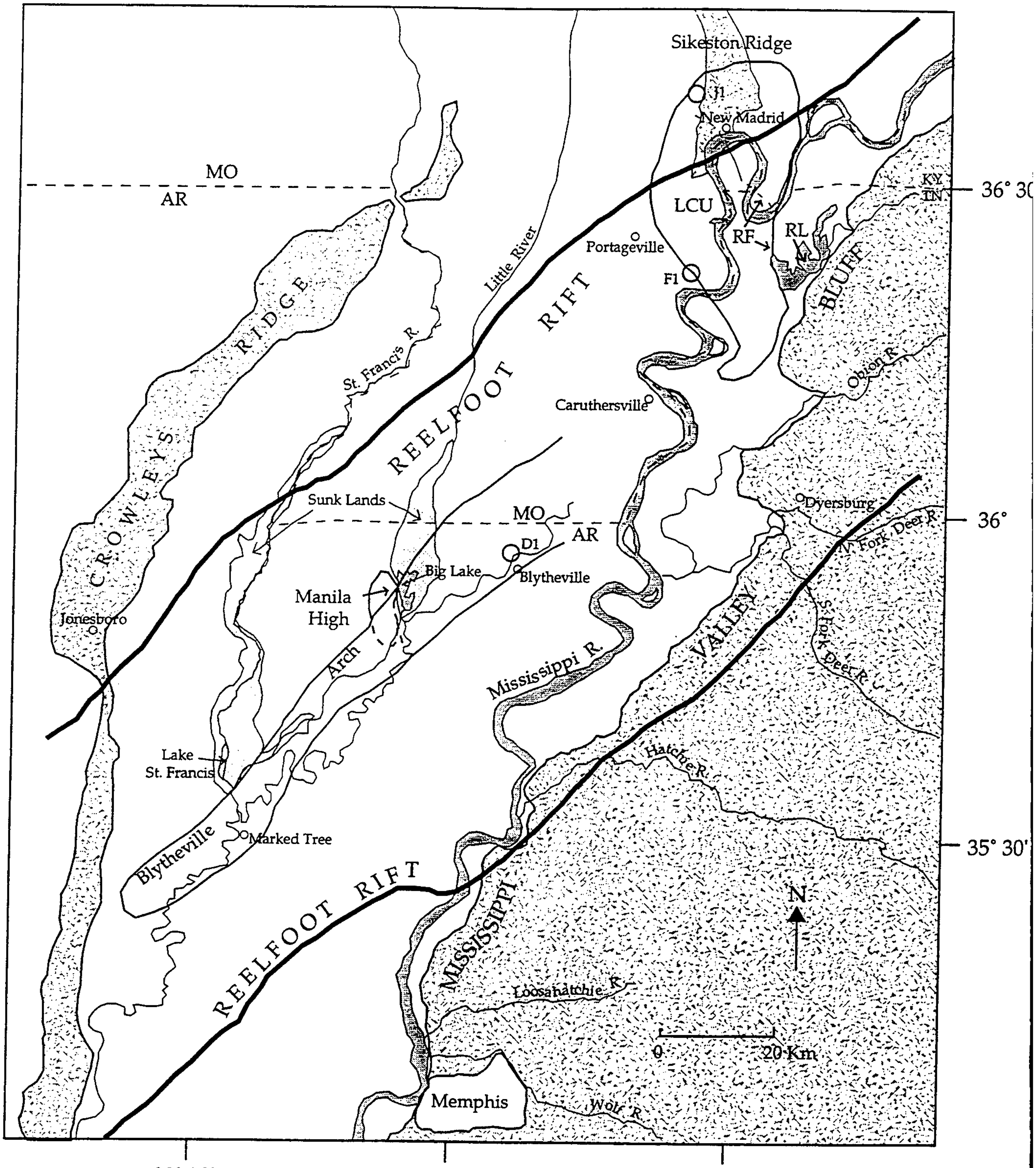


Figure 38. Map of major features of the Mississippi River valley. The Major earthquakes of 1811 -12 are designated as D1, J1, and F1 for December, January, and February.

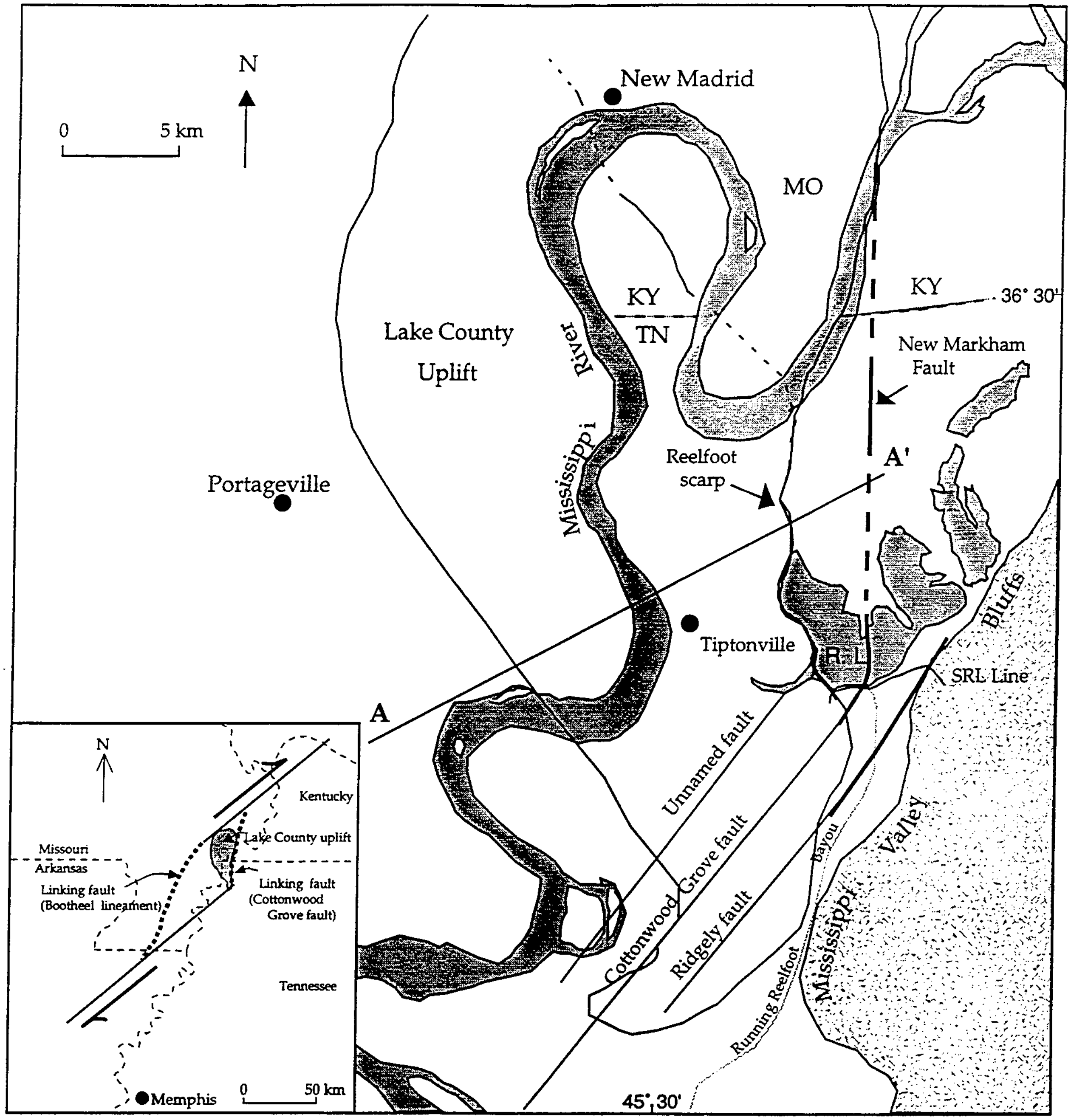


Figure 39. Location of the Lake County uplift boundaries, and interpreted fault traces. Dashed fault line is the projection of the Cottonwood Grove fault north to the New Markham fault zone. From Purser, 1996.

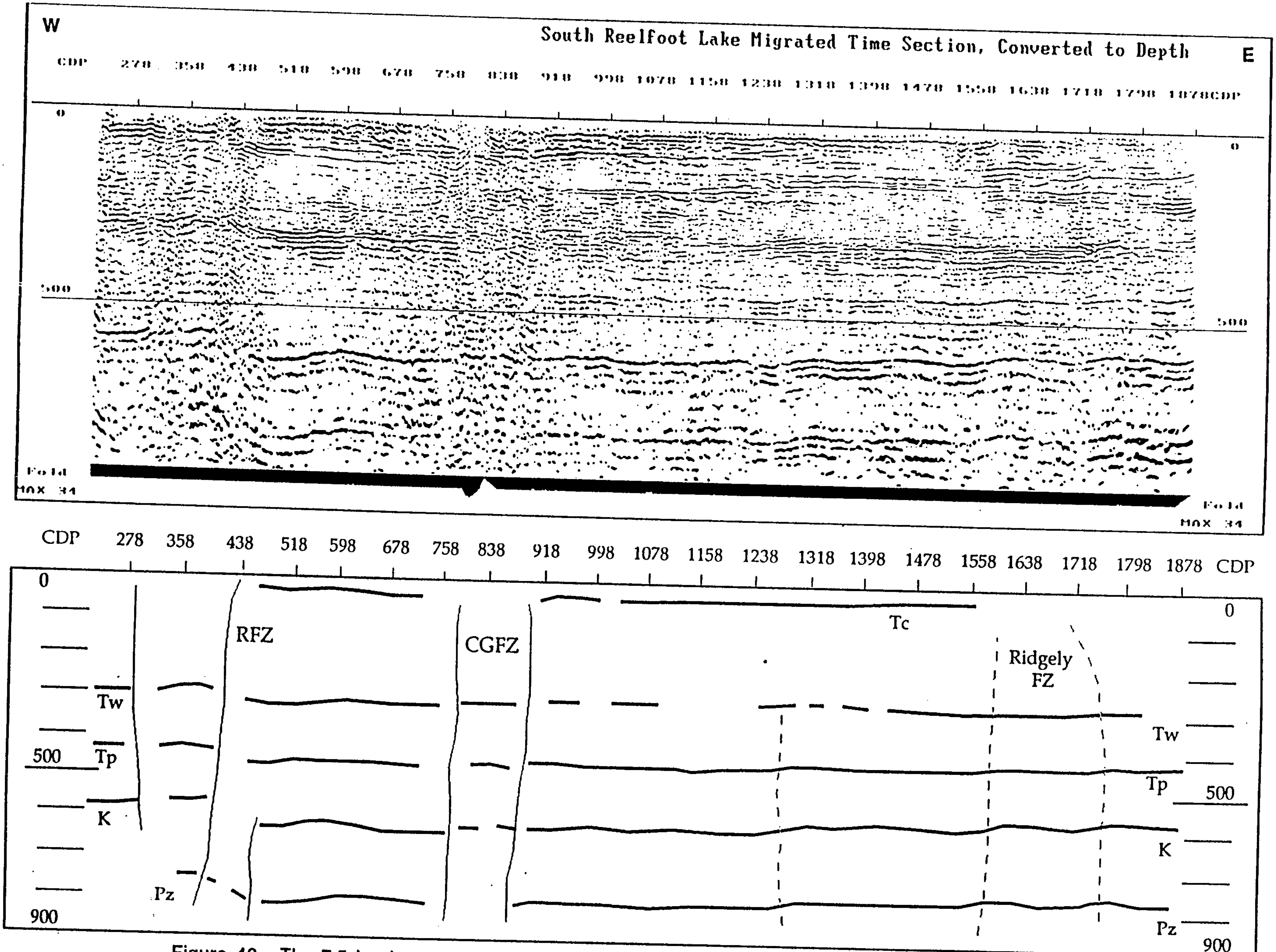
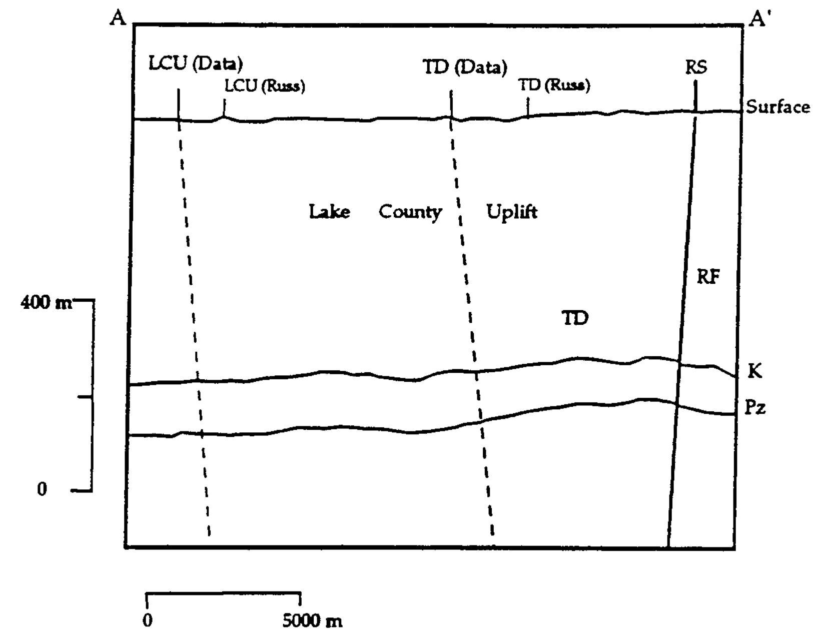


Figure 40. The 7.5 km long Reelfoot Lake Mini-Sosie (SRL) reflection profile. Vertical exaggeration is 2.7. The vertical axis is in meters. RFZ=Reelfoot fault zone, CGF=Cottonwood Grove fault, TC=Tertiary Claiborne

A



B

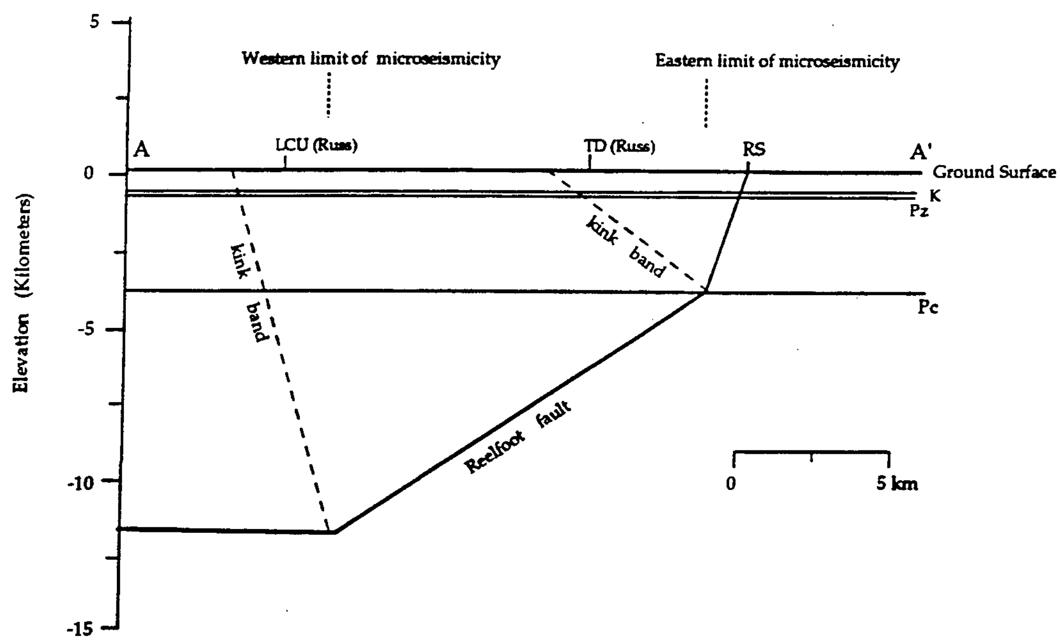


Figure 41. Northeast oriented cross section of the Lake County uplift. The western margin of the Lake County uplift and Tiptonville dome are marked as defined by Russ (1982) and in our data. The dashed lines are the proposed kink bands. K=top of the Cretaceous, Pz=top of the Paleozoic, RS=Reelfoot scarp, RF=Reelfoot fault. Vertical exaggeration is 15X in the A figure thus making the Reelfoot fault and kink bands nearly vertical. Figure B is cross section A-A' using the fault-bend fold model of Suppe (1985). Note there is no vertical exaggeration in B. K=top of Cretaceous, Pz=top of Paleozoic, Pc=top of Precambrian, LCU=Lake County uplift western margin (Russ, 1982), TD=Tiptonville dome western margin (Russ, 1982), RS=Reelfoot scarp. See Figure 39 for location. From Purser, 1996.

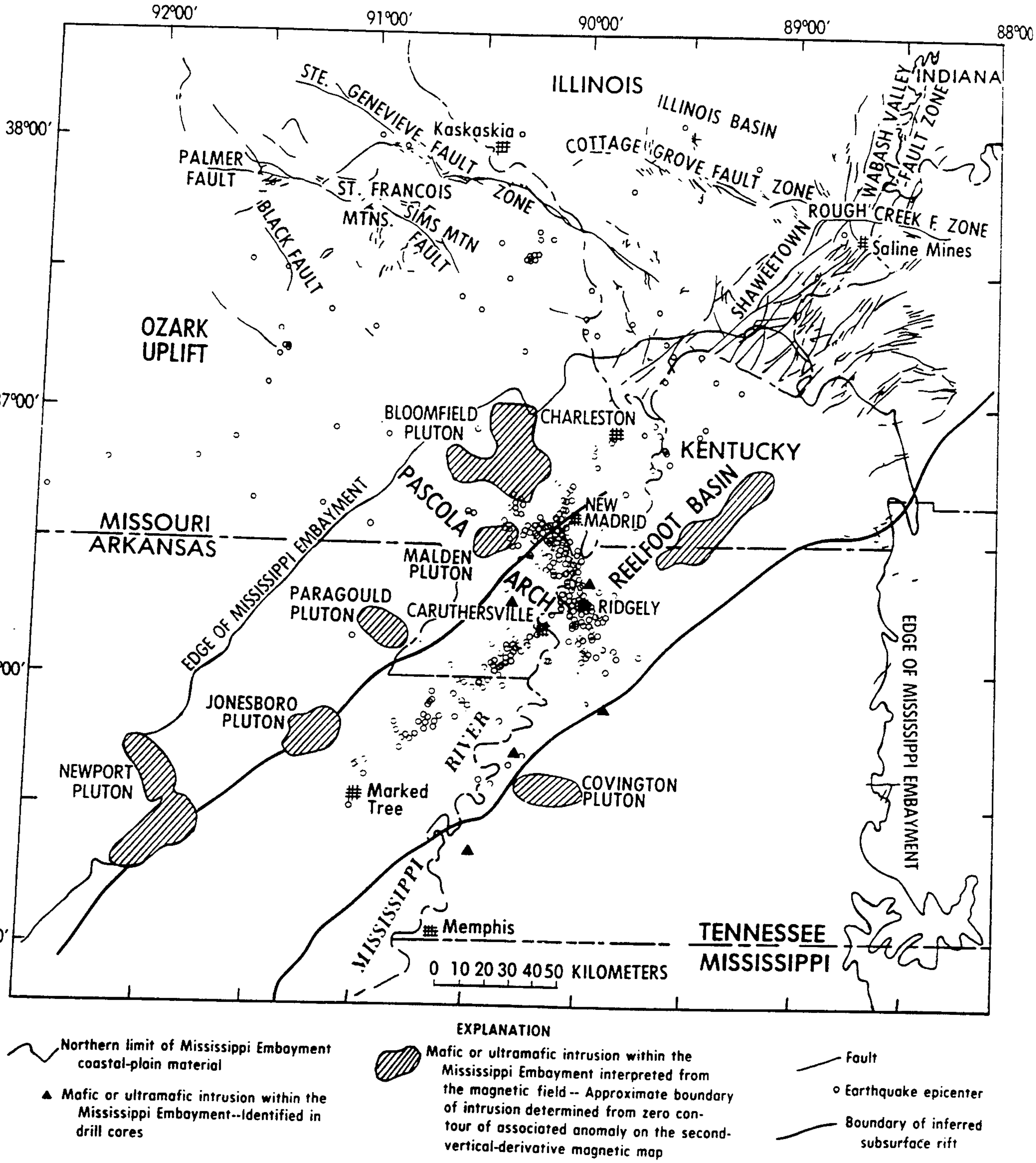


Figure 42. Generalized fault map of the New Madrid region showing plutons, approximate rift boundaries, and epicenters of earthquakes detected from July 1974 to June 1977. From McKeown, 1982.

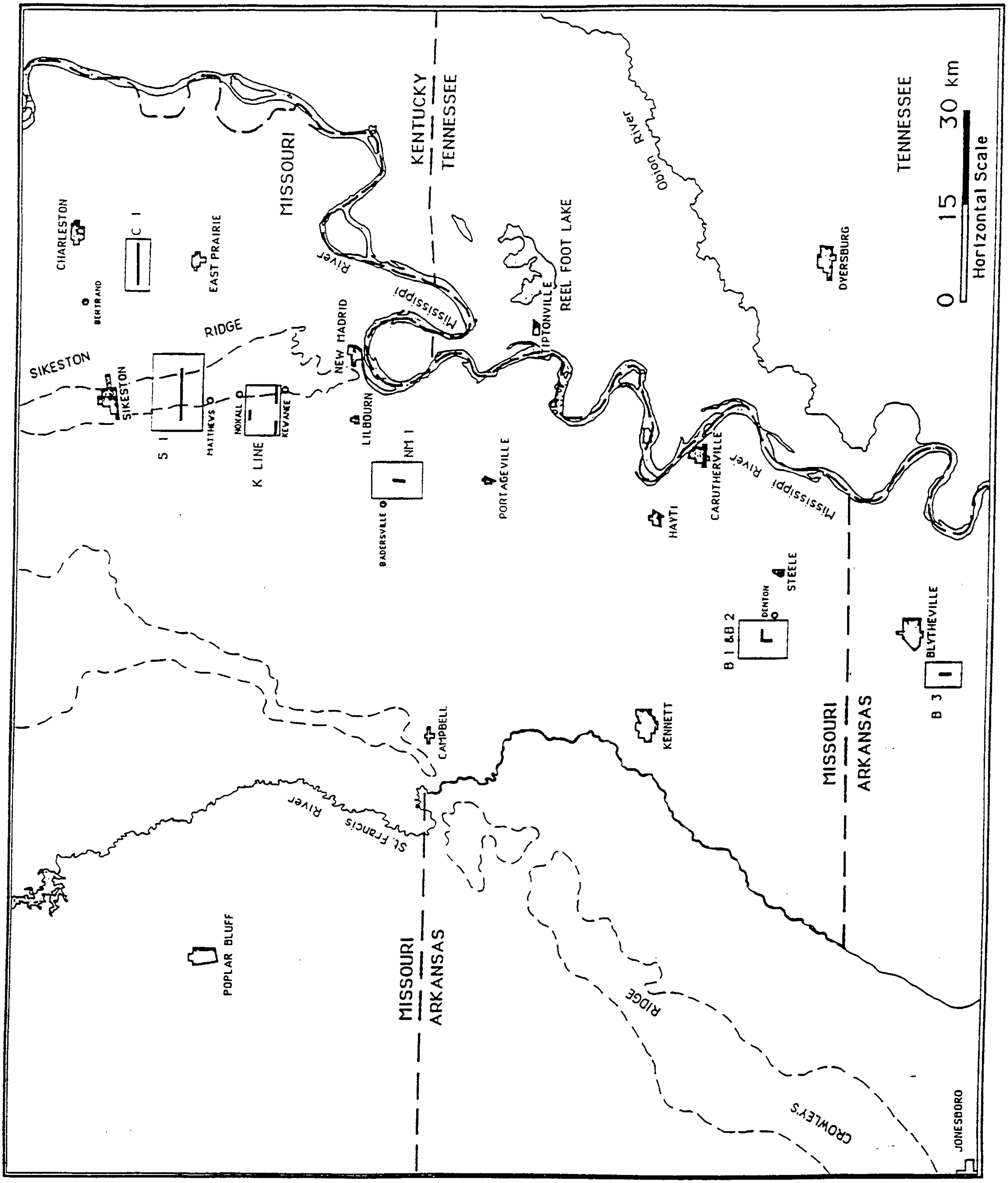


Figure 43. Regional map of study area showing location of the Mini-Sosie high resolution seismic lines. From Sexton, 1992.

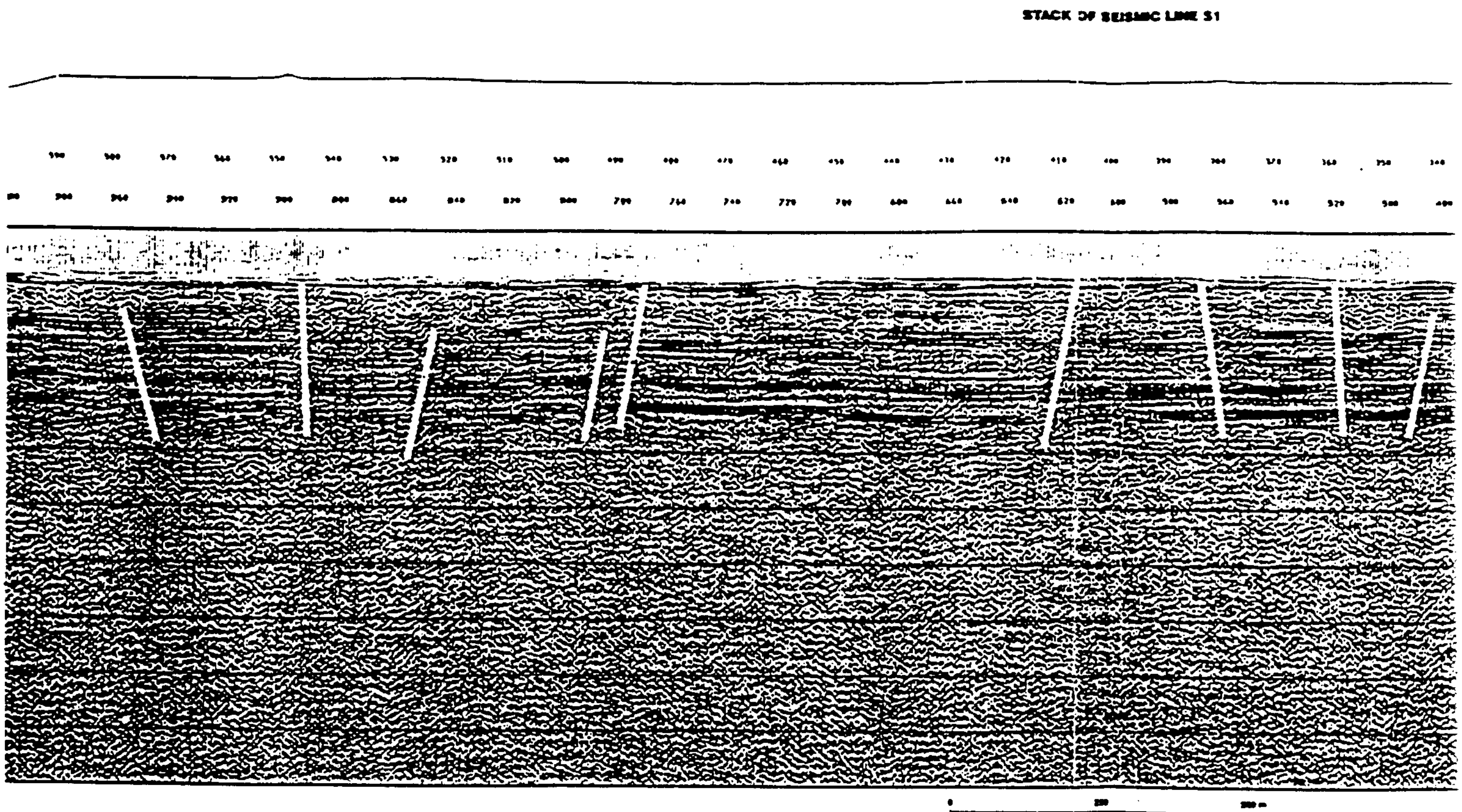
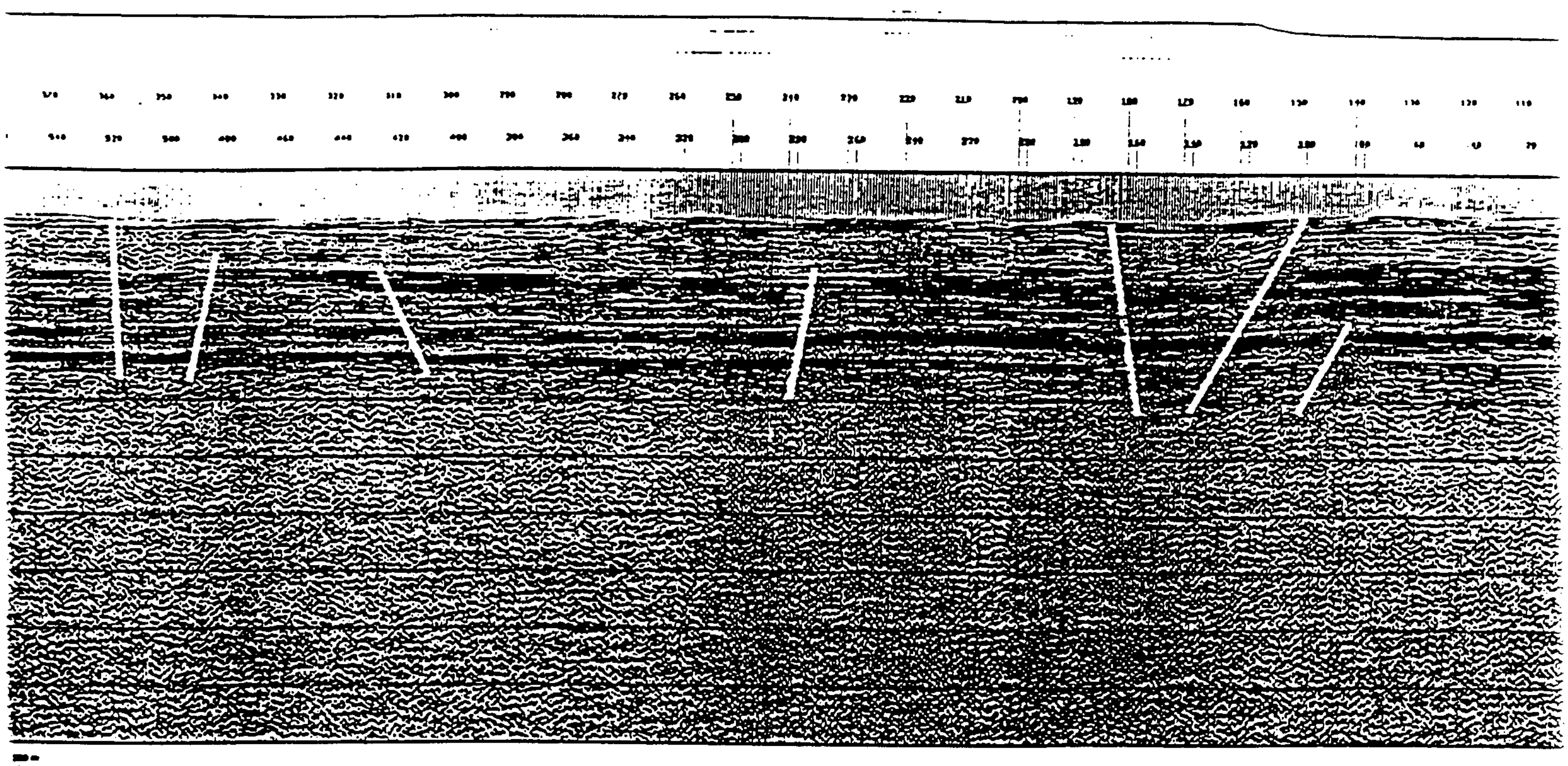


FIGURE 9

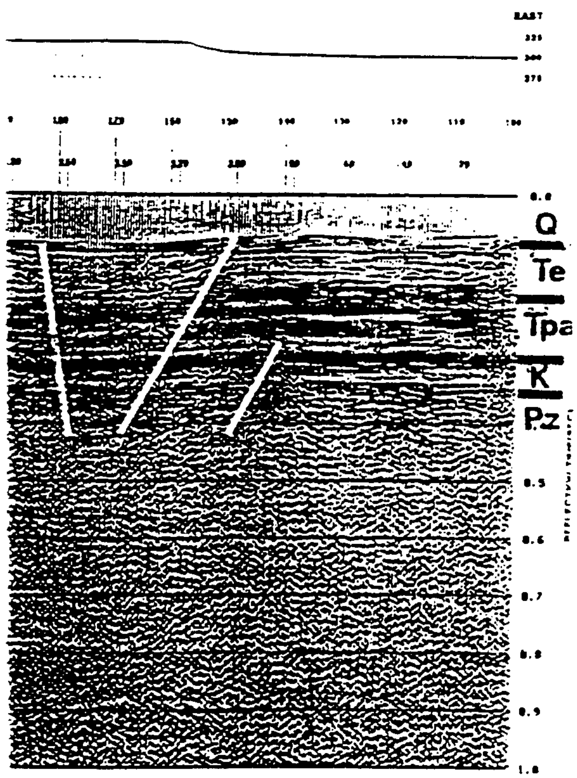
Figure 44. Interpreted final stacked section of seismic line S1. Approxima
Paleozoic-Cretaceous unconformity is 440 m in the region just east of Sikes
Figure 43 for location. From Sexton, 1992.

1



S1. Approximate depth to the
st east of Sikeston Ridge. See

(2)



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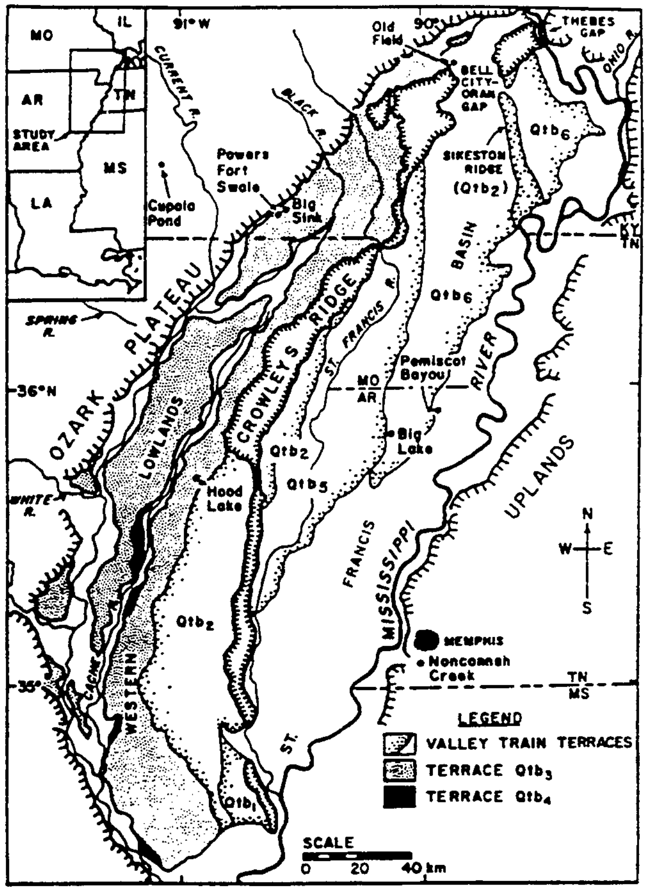

Figure 45. Quaternary geomorphic surfaces within and adjacent to the central Mississippi alluvial valley. Four braided-stream terraces are mapped within the Western Lowlands: Qtb_1 of late Illinoian Age, Qtb_2 of early to middle Wisconsinan Age, and Qtb_3 and Qtb_4 of late Wisconsinan Age. The Cache River terrace (Qtc) of late Wisconsinan/early Holocene Age (?) is not shown at this scale. Three braided stream terraces are mapped within the St. Francis Basin of the Eastern Lowlands: Qtb_2 of early to middle Wisconsinan Age and Qtb_5 and Qtb_6 of late Wisconsinan/early Holocene Age. Terrace Qtb_3 is mapped using the dense stippled pattern, terrace Qtb_4 is mapped using black, and all other braided stream terraces are shown using a light stippled pattern for valley train terraces (from Royall et al., 1991). Evident in this map are the broad terraces on either side of Crowley's Ridge with the modern Mississippi River on the extreme eastern side of the Mississippi Valley and Black-White river system (location of the ancestral Mississippi River) on the extreme western side of the Mississippi valley. From Van Arsdale et al., 1995a.

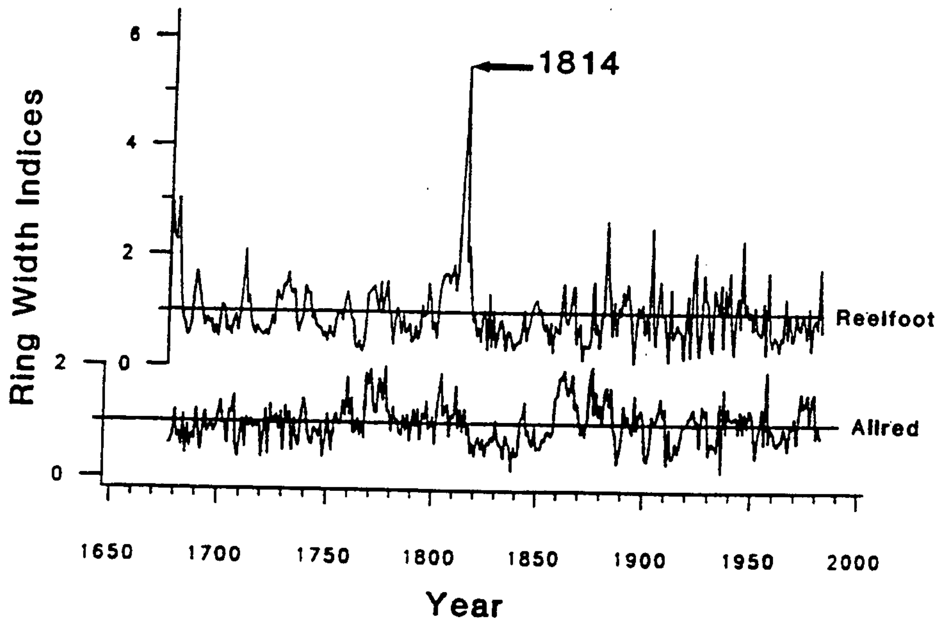

Figure 46. Standardized Baldcypress tree-ring chronologies from Reelfoot Lake, Tennessee, and Allred Lake, Missouri. These mean ring-width index chronologies are dimensionless indices of growth for each year. Biological or age-related growth trends were removed and each core series was indexed before averaging into the chronology. Growth trend was not entirely removed from two cores that comprise the first 5 years of the Reelfoot Lake chronology. From Stahle et al., 1992.

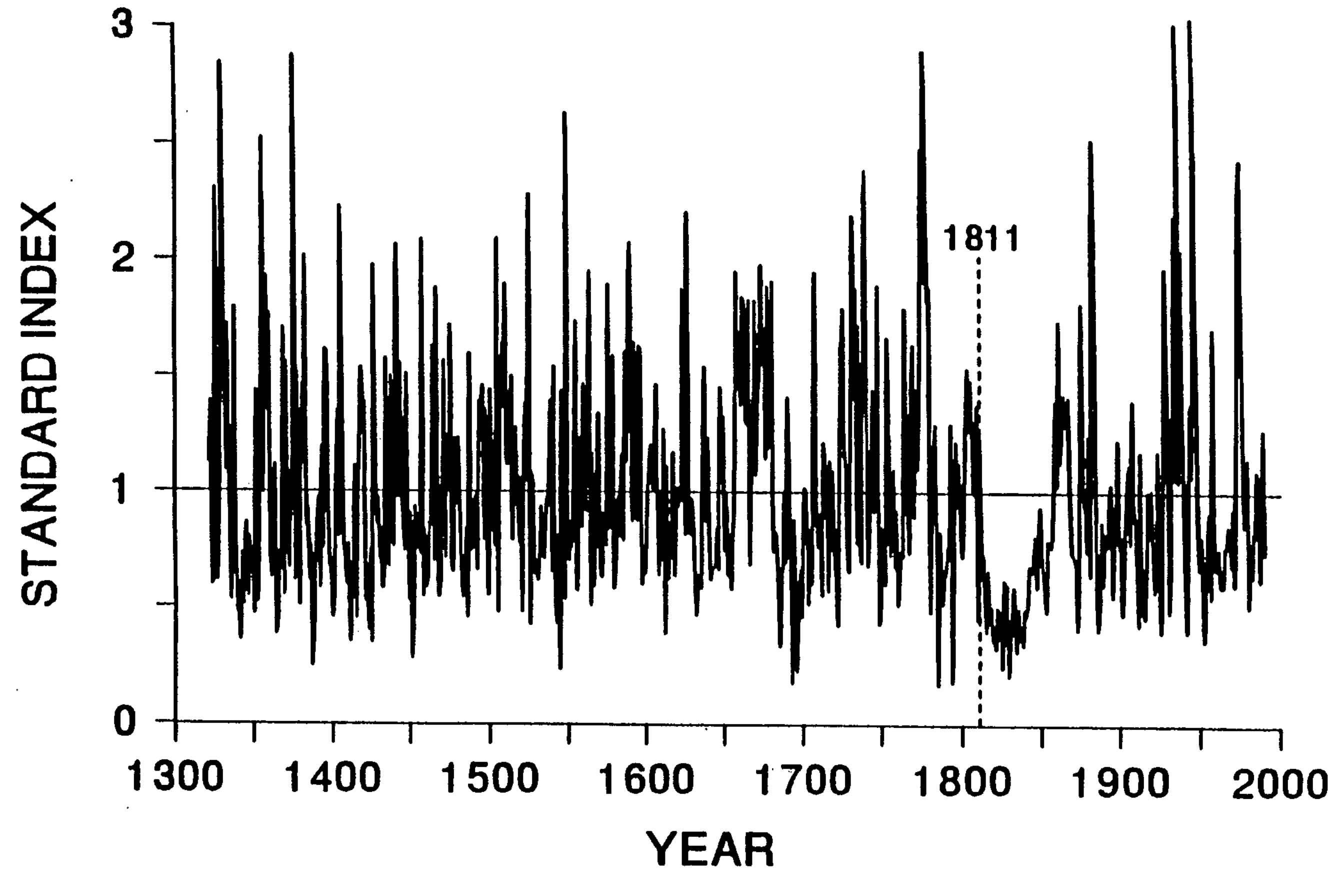

Figure 47. Plot of the St. Francis Sunk Lands Baldcypress tree-ring chronology from 1321-1990. From D. Stahle and M. Cleaveland, unpublished.

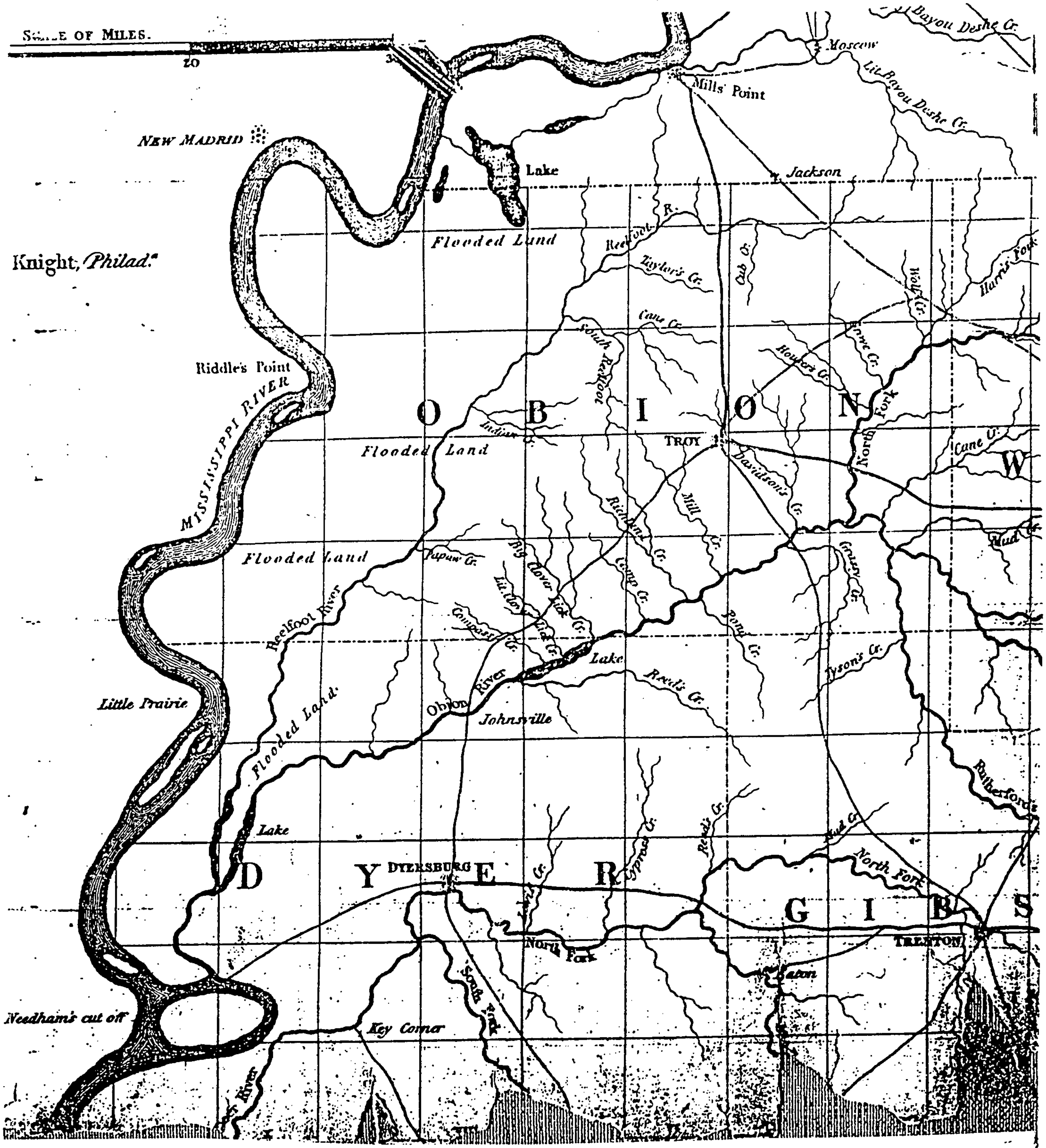

Figure 48. Lake formed on the Obion River in northwestern Tennessee during the 1812 New Madrid earthquake. Each block is 5 miles on a side. From Rhea, 1832.

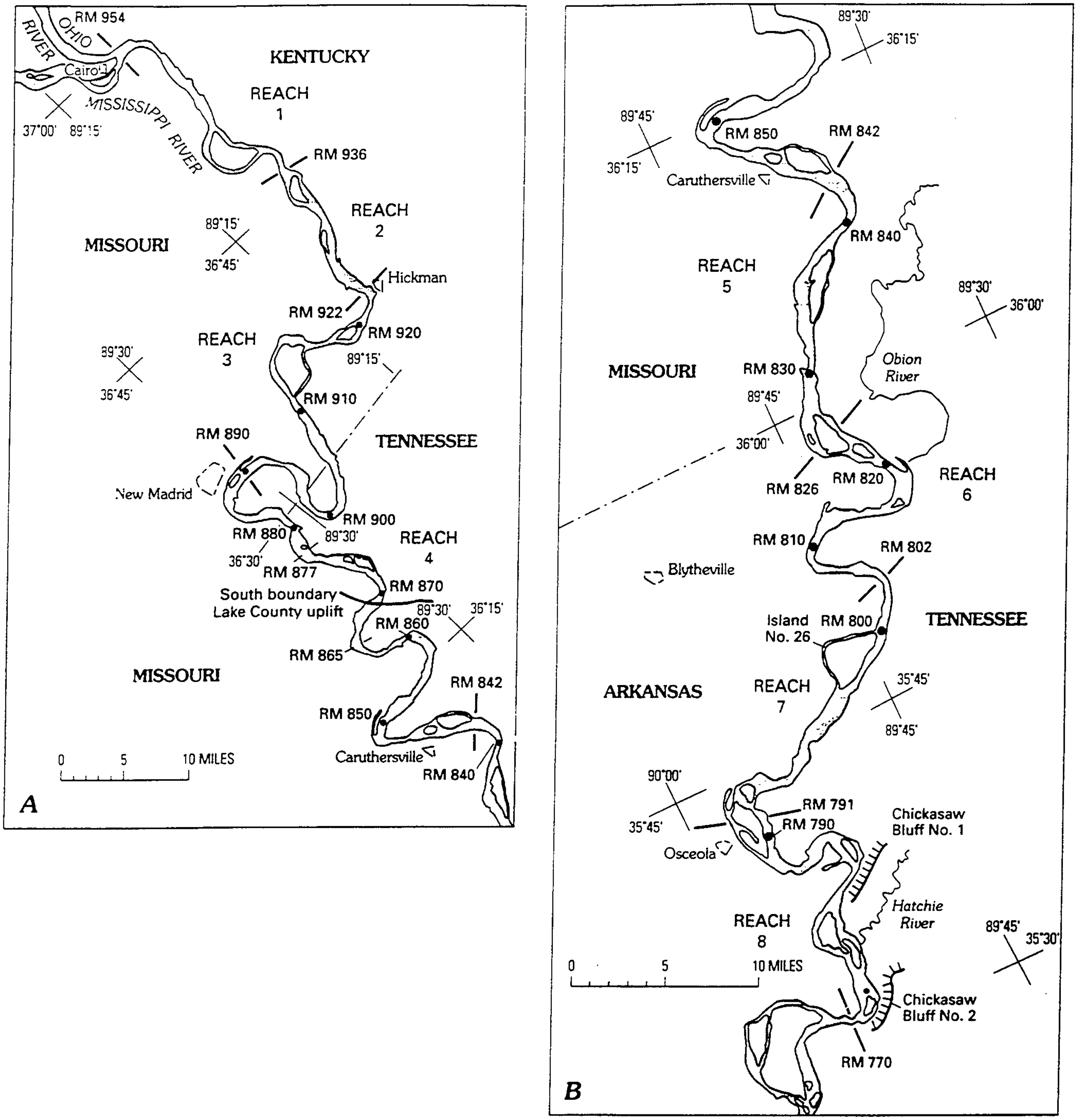

Figure 49. Mississippi River reaches. RM=river mile. From Boyd and Schumm, 1995.

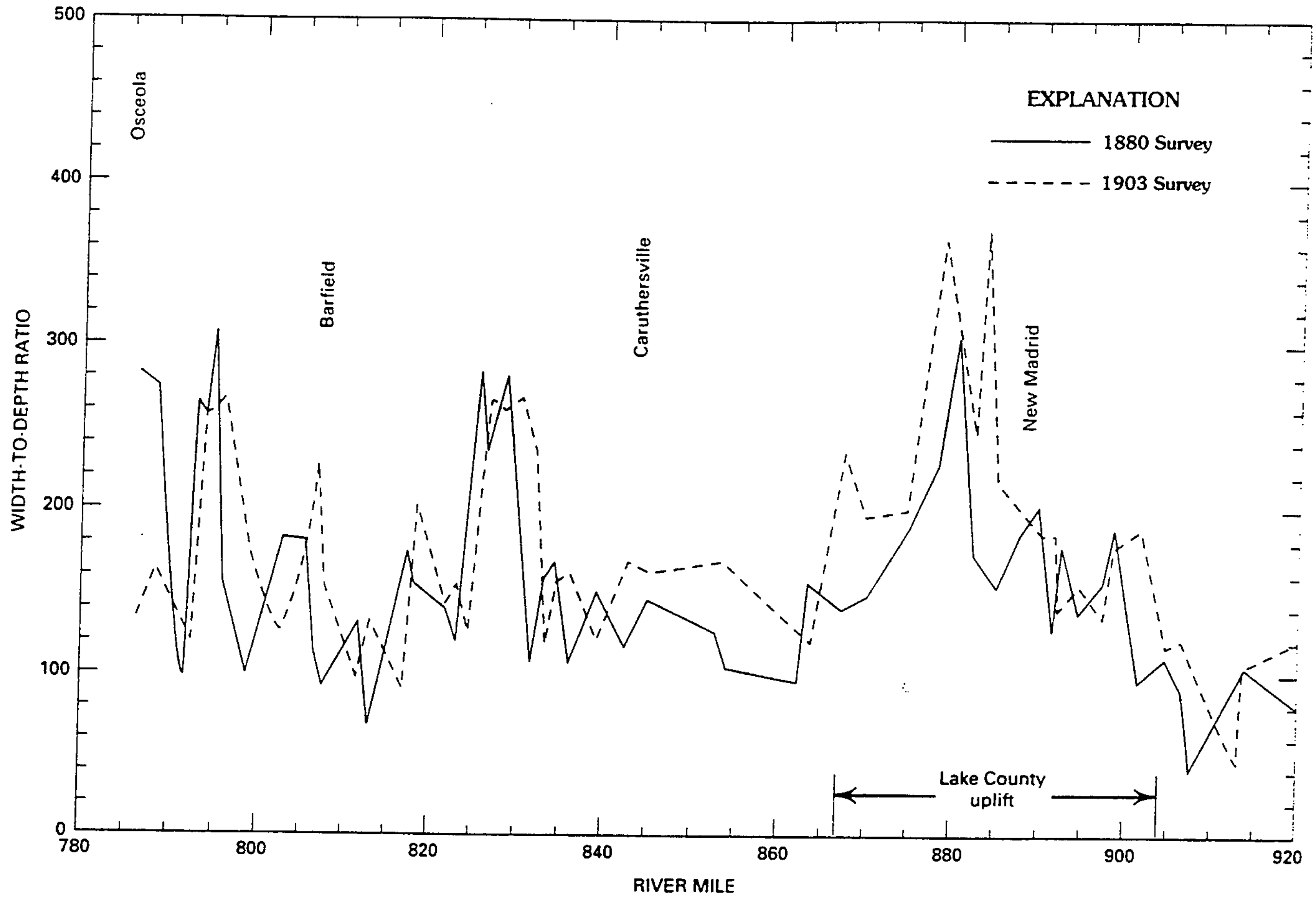

Figure 50. Channel width-to-depth ratios of the Mississippi River plotted against river mile for 1880 and 1903 surveys. From Boyd and Schumm, 1995.

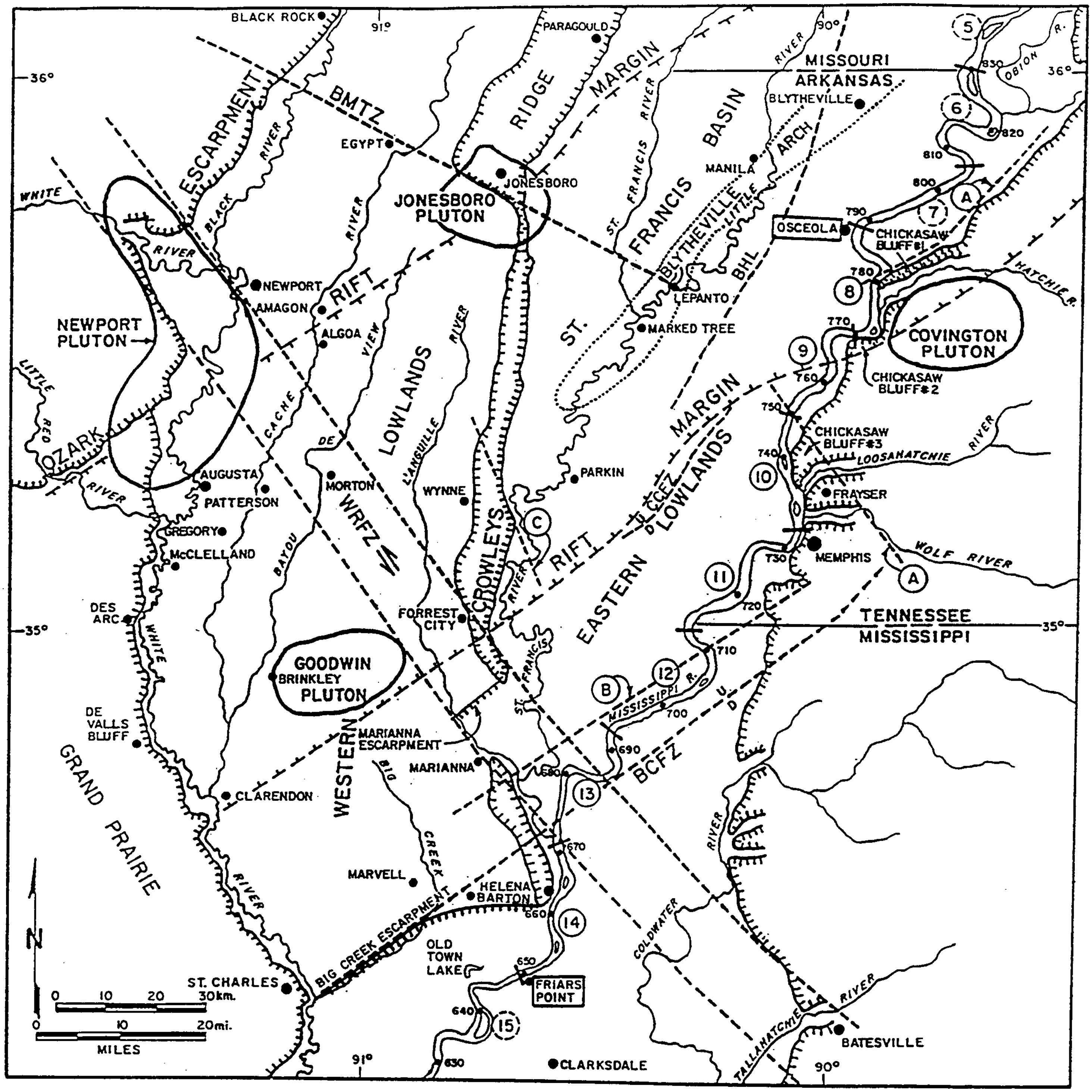

Figure 51. Index map of the alluvial valley of the Mississippi River between Blytheville, Arkansas and Clarksdale, Mississippi. Numbers indicate Mississippi River reaches based on 1880 maps. Circled letters represent inferred faults within the study area. BMTZ=Bolivar-Mansfield tectonic zone, WRFZ=White River fault zone, BCFZ=Big Creek fault zone; CCFZ=Crittenden county fault zone, BHL=Bootheel lineament. From Spitz and Schumm, 1997.

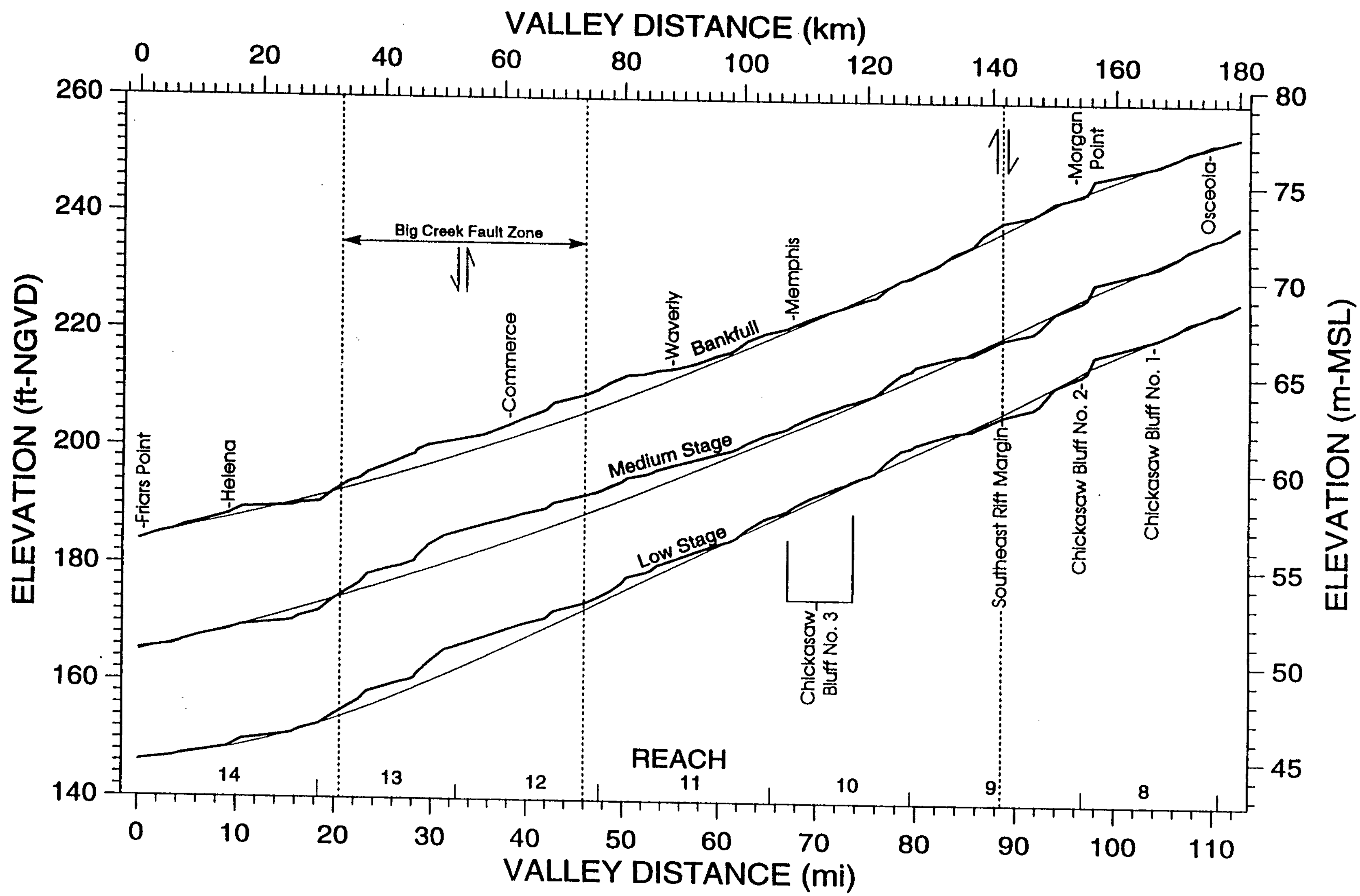

Figure 52. Bankfull, medium, and low stages of the Mississippi River plotted against valley mile (projected profiles). Reference lines represent a hypothetical smooth profile. Data are from 1880 surveys, which are prior to major human modification of the river. From Spitz and Schumm, 1997.

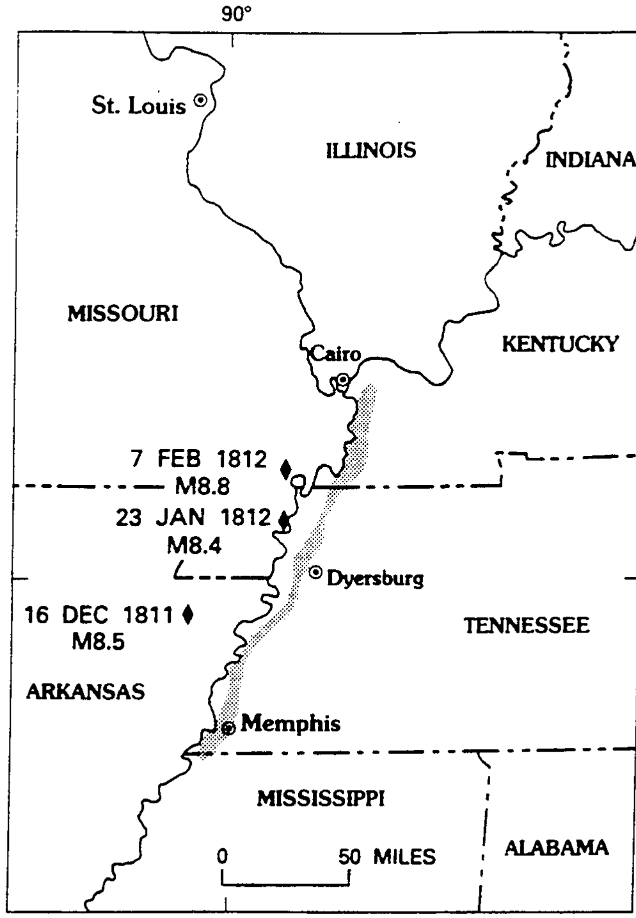

Figure 53. Landslide area (shaded) along the eastern bluffs of the Mississippi Valley. From Jibson and Keefer, 1988.

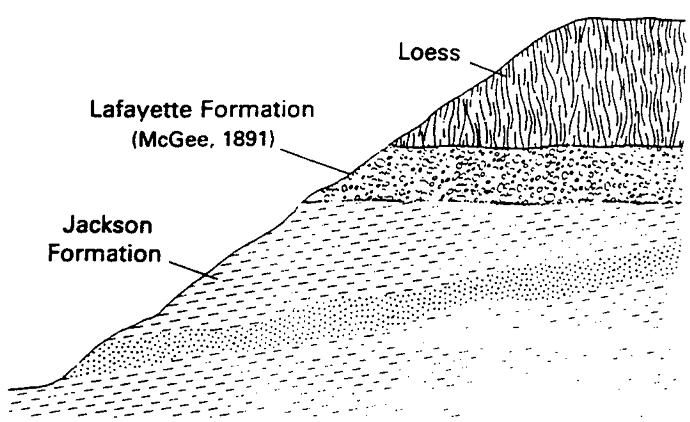

Figure 54. Generalized structure and stratigraphy of the eastern bluffs of the Mississippi Valley. From Jibson and Keefer, 1988.

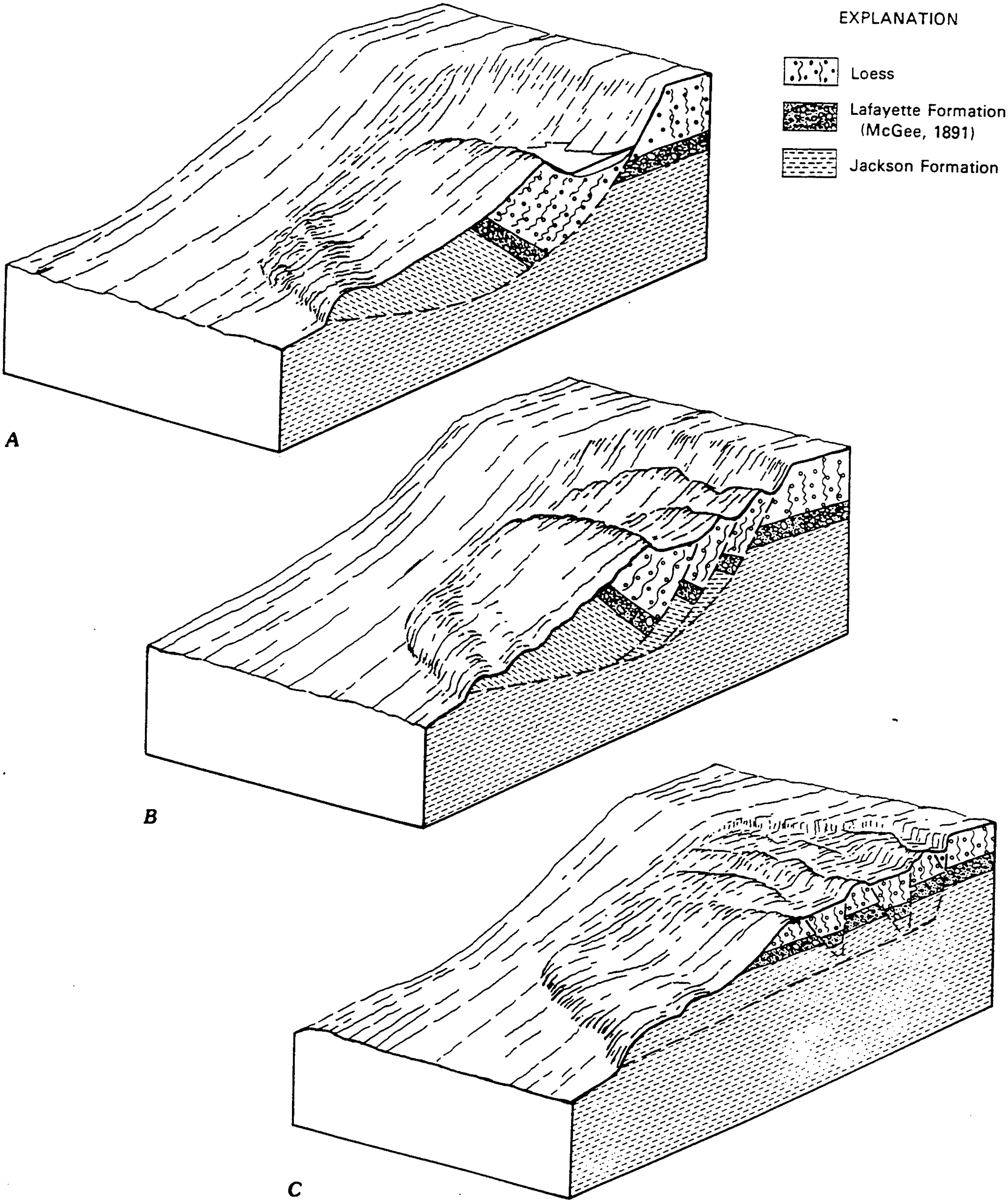

Figure 55. Idealized drawings of types of old coherent slides along the eastern bluffs of the Mississippi Valley. These landslides all have eroded, revegetated features, and no active analogs are present in the area. A, Single-block rotational slump; B, multiple-block rotational slump, C, translational block slide. From Jibson and Keefer, 1988.

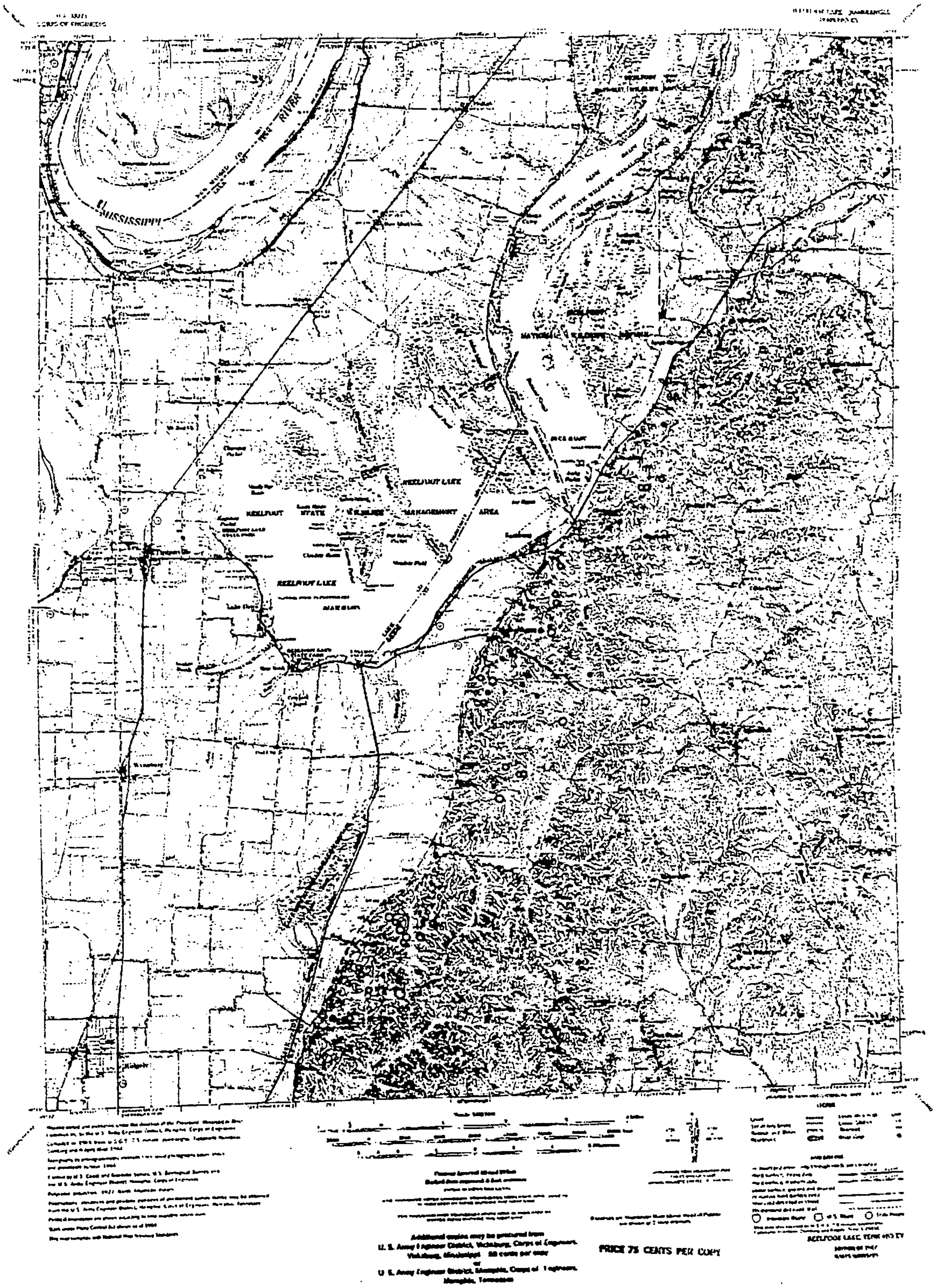

Figure 56. Location of 56 craters on the eastern bluffs of the Mississippi Valley. From Dennon, 1990.

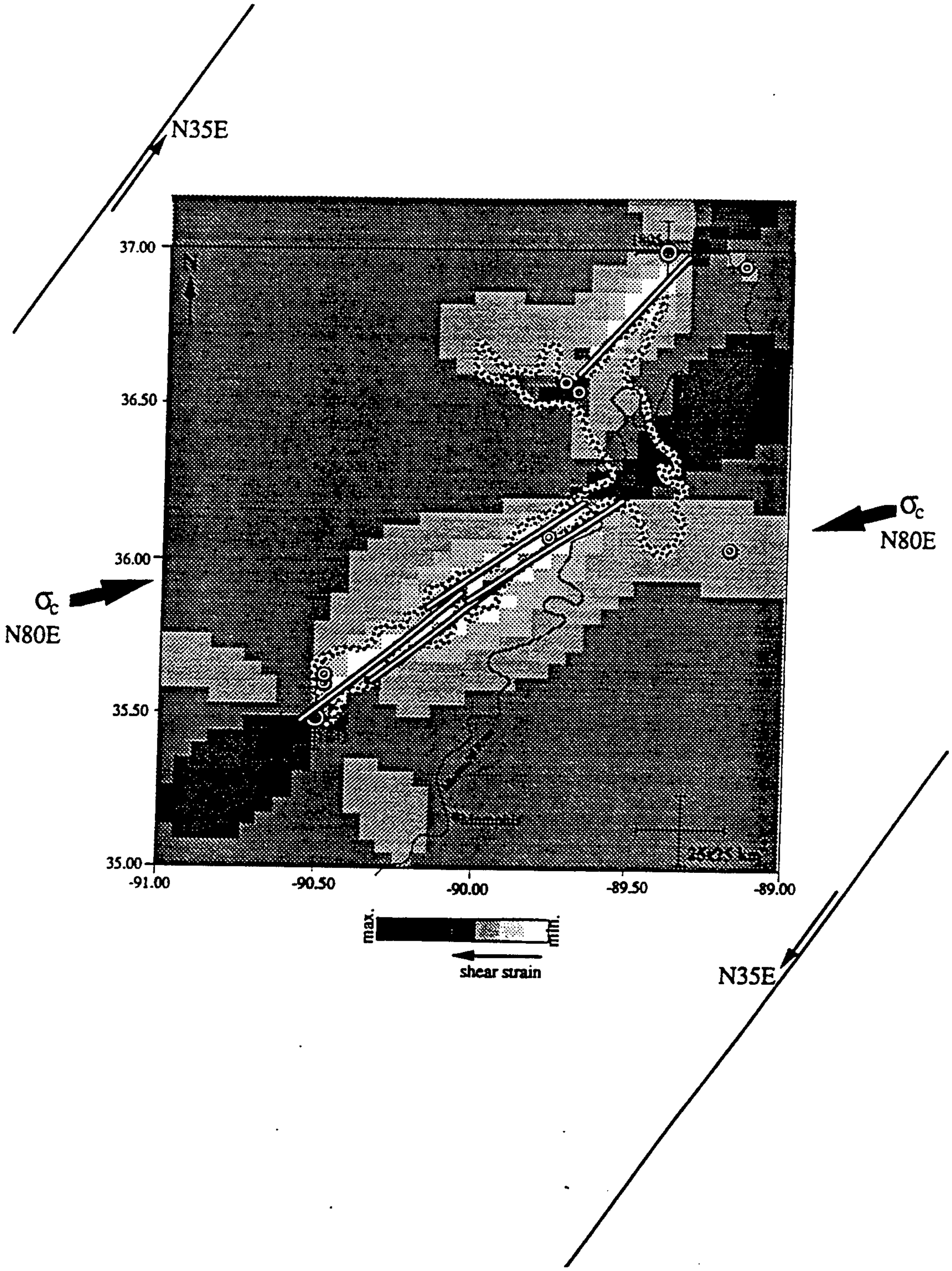

Figure 57. Right-lateral shear strains at azimuths of N42^{0}E which is the average strike of the inferred primary faults of the NMSZ. These are calculated for a model in which secondary faults slip freely in response to the uniform regional strain field. The pattern of strains is essentially the same for strikes $\pm25^0$ from N42^{0}E. From Gomberg, 1993.

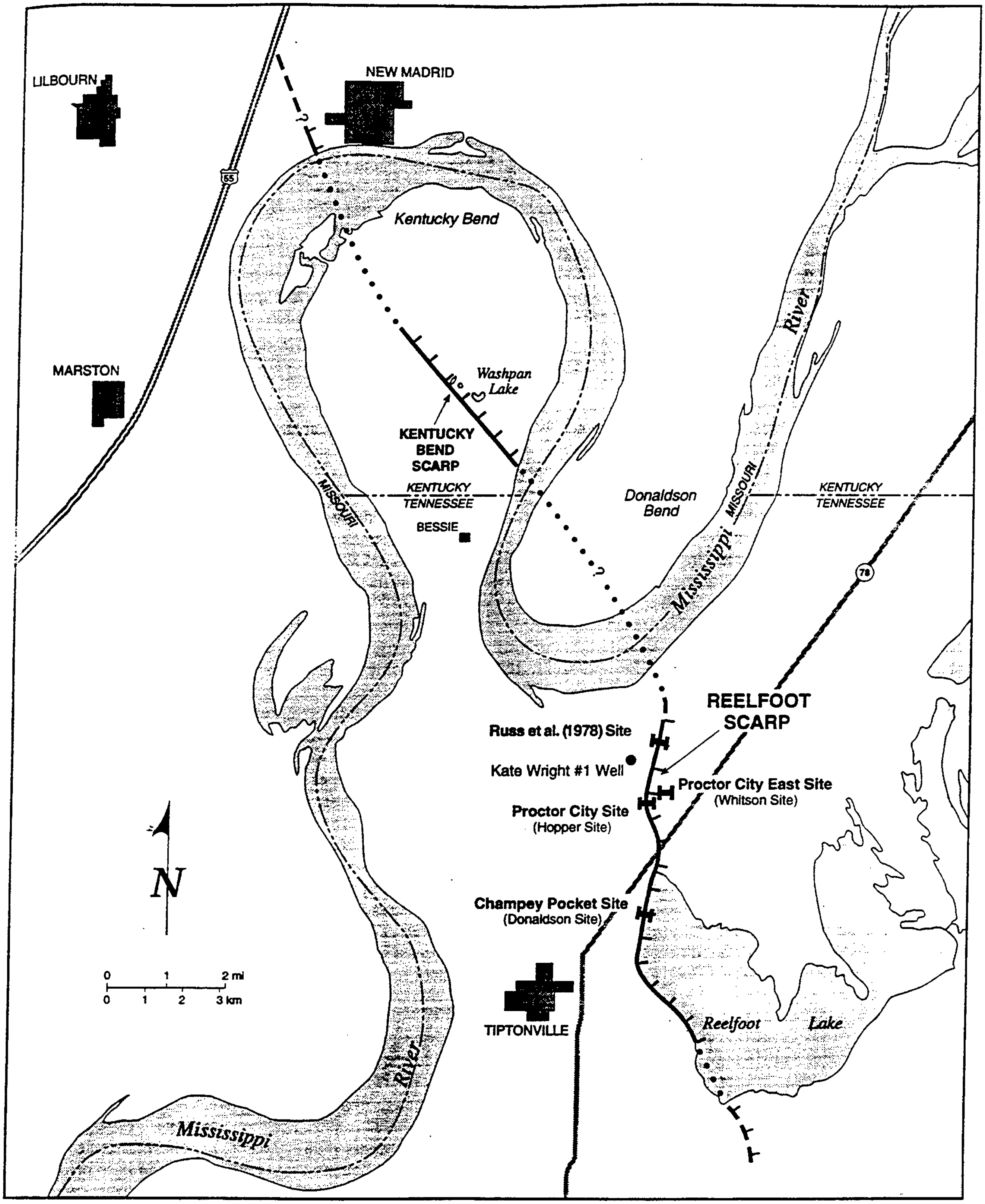

Figure 58. Location map showing the Reelfoot scarp (dotted where beneath Reelfoot Lake or eroded, dashed where inferred), the Kentucky Bend scarp, and trench sites. From Kelson et al., 1996.

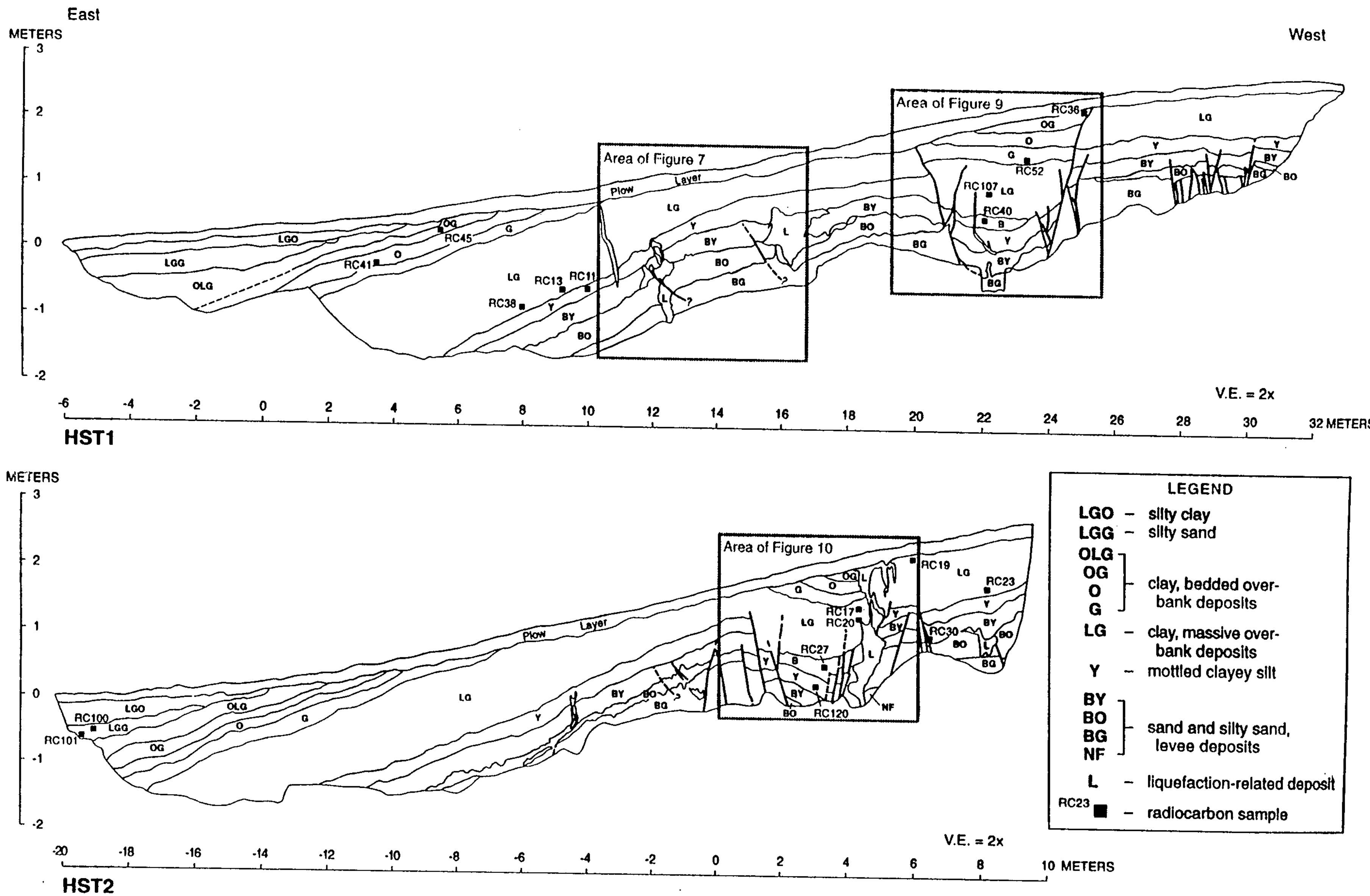

Figure 59. Generalized logs of southern walls of trenches HST1 and HST2 at the Proctor City site. See Figure 58 for location. From Kelson et al., 1996.

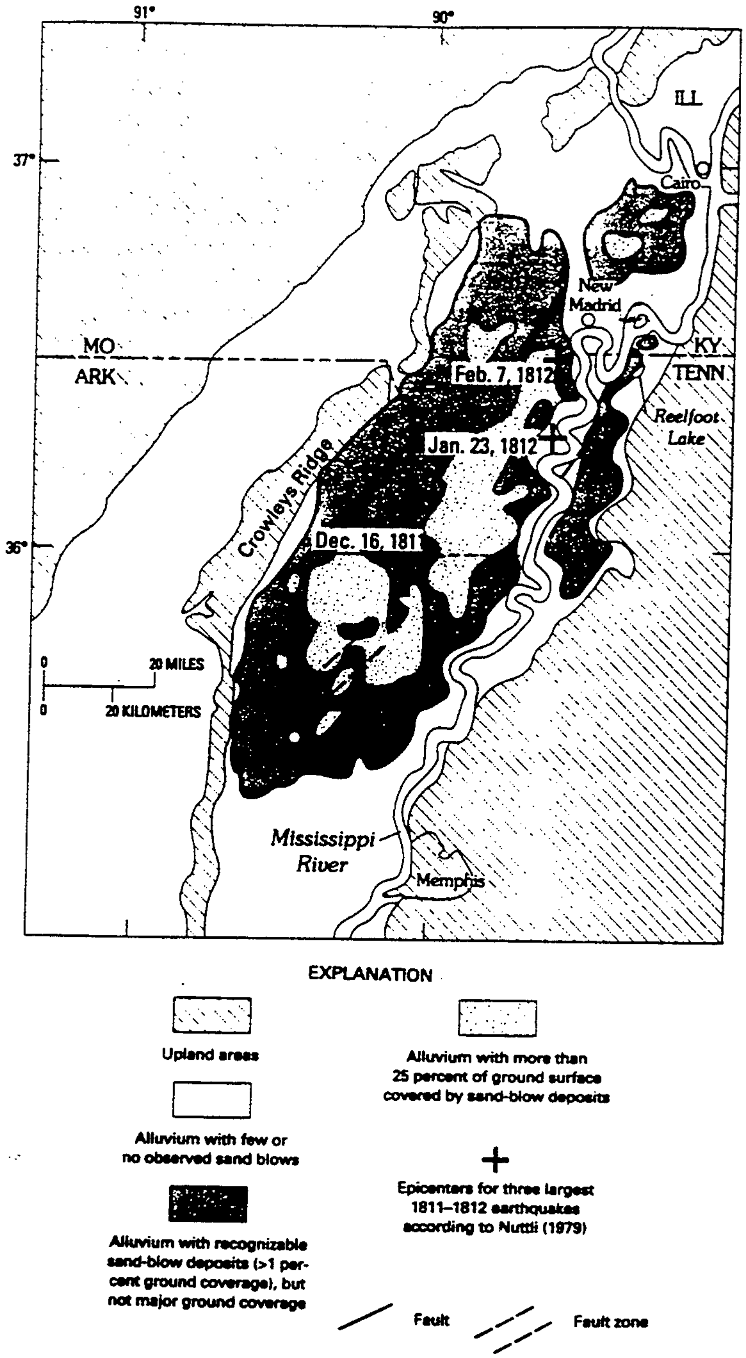

Figure 60. Regions having abundant vented sand, excluding modern floodplains, in the New Madrid seismic zone. Sand was presumably vented in response to the 1811-12 earthquakes. Severe liquefaction also occurred locally beyond the areas shown on the map, especially along streams west of Crowley's Ridge. From Obermeier, 1996.

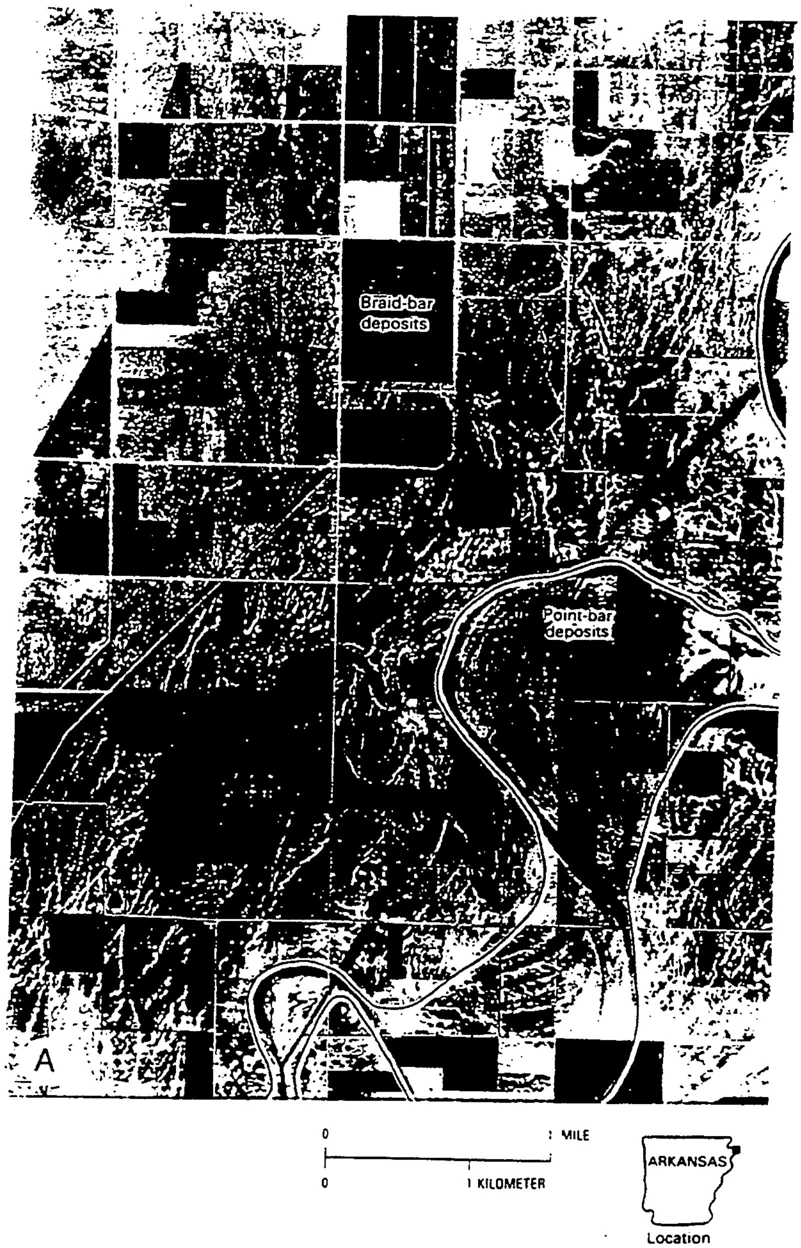

Figure 61. Aerial photograph near Manila, Arkansas, that shows long fissures (dikes) through which sand vented (light-colored linear features) and also individual sand blows (light-colored spots) formed by liquefaction during the 1811-1812 New Madrid earthquakes. Fissuring and venting took place in braid-bar deposits of latest Pleistocene age and in younger Holocene point-bar sediments. Note how fissures formed parallel to the scrolls of point-bar deposits. Note also the abundance of fissures in the upper part of the right side of the photograph. These fissures have formed near a break in slope, where the terrace that is underlain by braid-bar deposits is adjacent to the slightly lower floodplain level of point-bar deposits. From Obermeier, 1996.

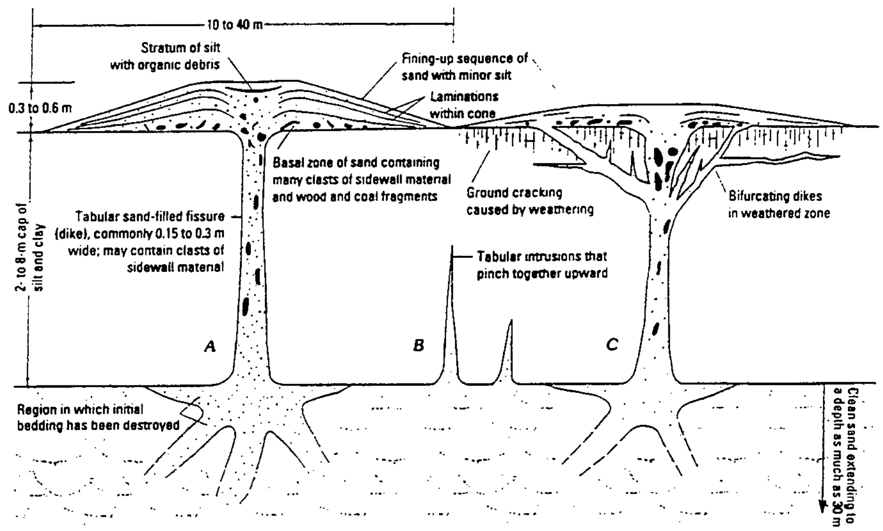

Figure 62. Schematic vertical section showing dikes cutting through overbank silt and clay strata and the overlying sand-blow deposits. (A) Stratigraphic details of sediment vented to the surface. (B) Dikes that pinch together as they ascend. (C) Characteristics of dikes in fractured zone of weathering, in highly plastic clays. From Obermeier, 1996.

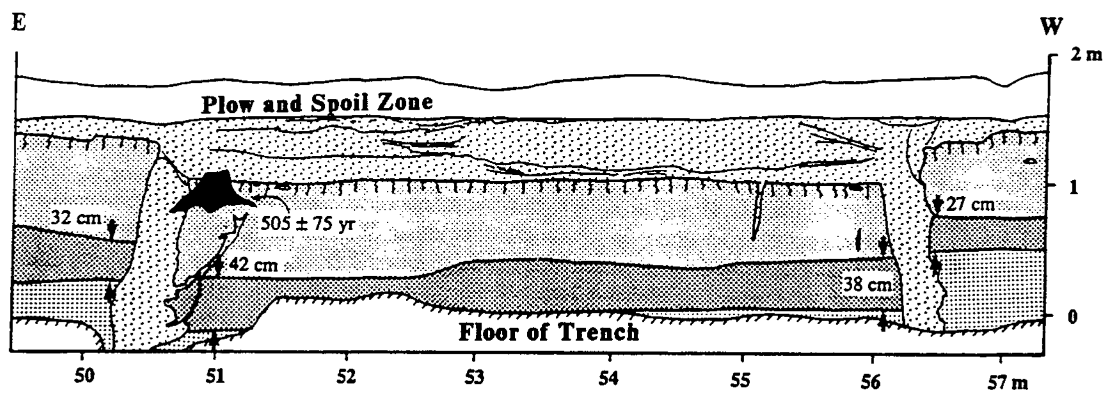

Figure 63. Log of part of trench across Bootheel lineament. At this site, lineament has no topographic expression, but is marked by a linear sand body. Downdropped block between two sand dikes underlies trace of lineament. From Schweig et al., 1992.

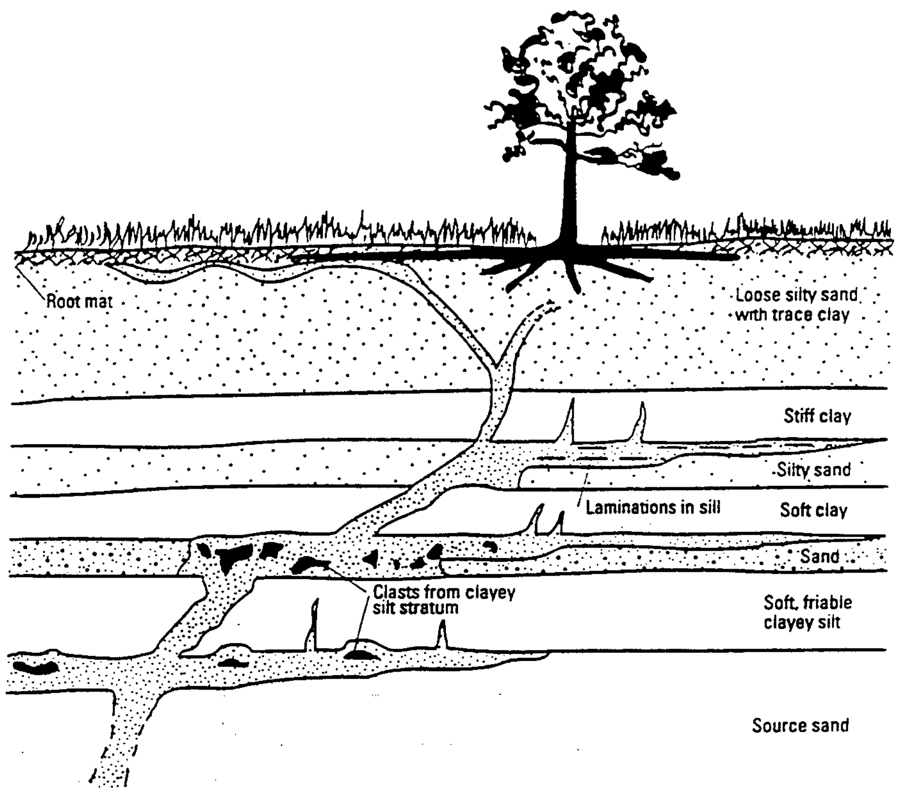

Figure 64. Schematic vertical section showing where sills form preferentially. Note that thin sills can extend great distances horizontally, especially where the overlying cap is thin. Such severe sill development as shown in the figure is typically accompanied by large sand blows. From Obermeier, 1996.

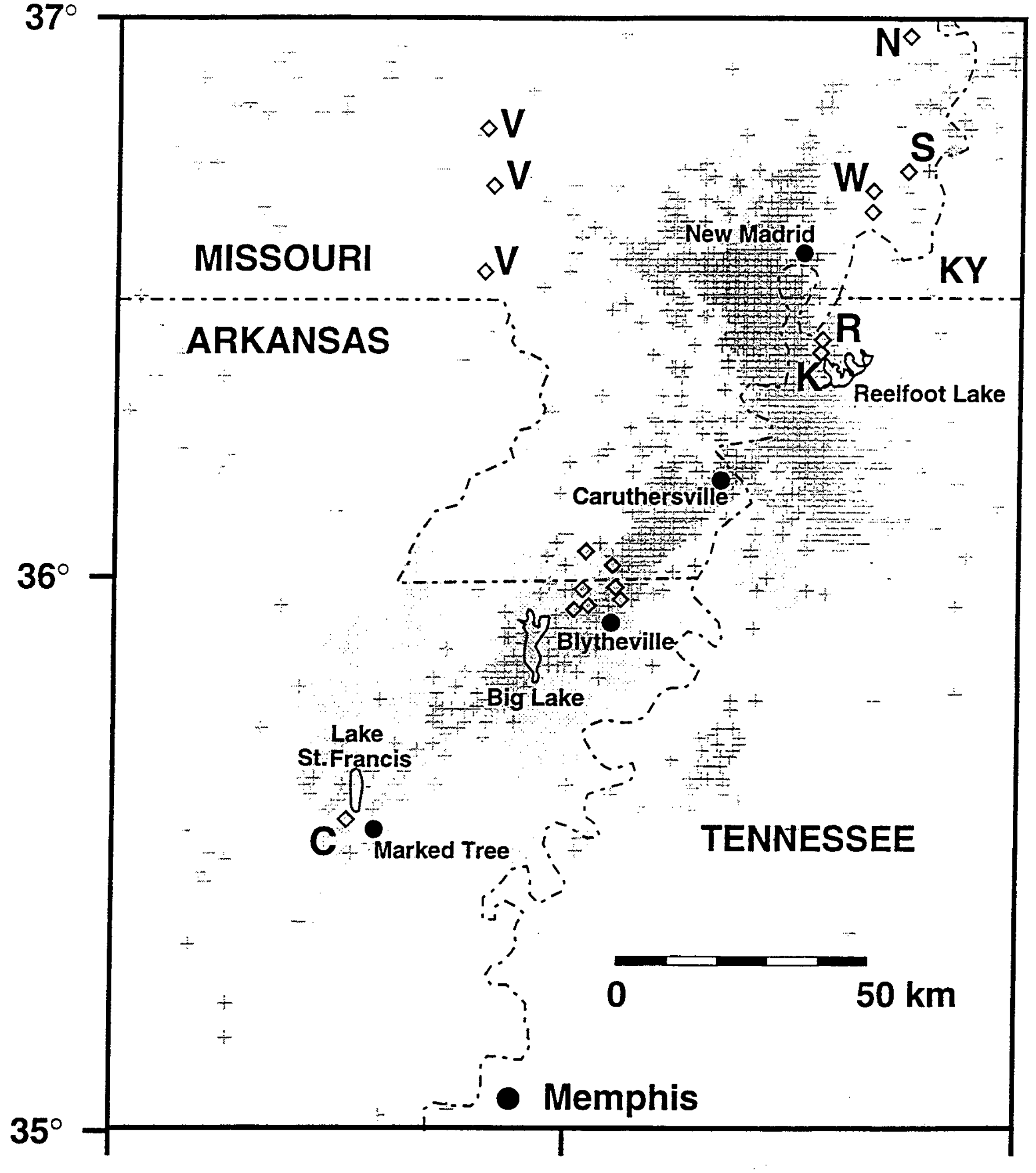

Figure 65. Sites of NMSZ paleoearthquake studies. Shading represents >1% of area covered by sand-blow deposits. Gray diamonds indicate sites at drainage ditches or trenches displaying prehistoric earthquake features: R=Russ (1982), K=Kelson et al. (1992, 1996), S=Saucier (1991), and V=Vaughn (1991). N and W described in Li et al. (1994). C and sites near Blytheville described in Tuttle and Schweig (1995) and Lafferty et al., (1996). From Schweig and Van Arsdale, 1996.

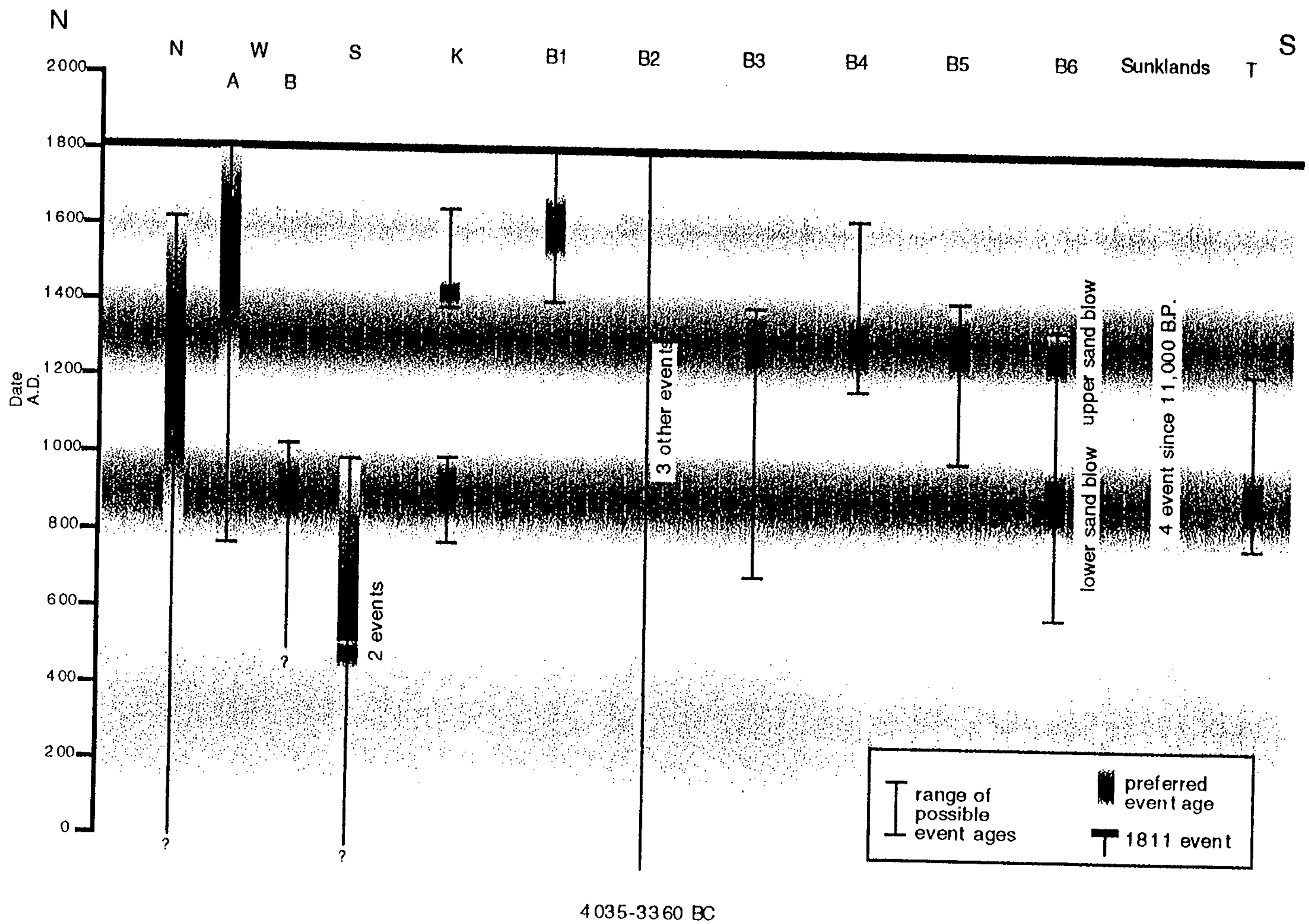

Figure 66. Summary of paleoearthquake investigations in the New Madrid seismic zone. Vertical bars and lines show results from individual sites or studies, generally arranged from north on the left to south on the right. Thick horizontal line at top represents the 1811-1812 sequence. Horizontal shaded bands represent likely age ranges of earthquakes in the past 2000 years, with darker shading representing the more likely dates. No implication of the magnitudes or area affected by the earthquakes is intended. From Johnston and Schweig, 1996.

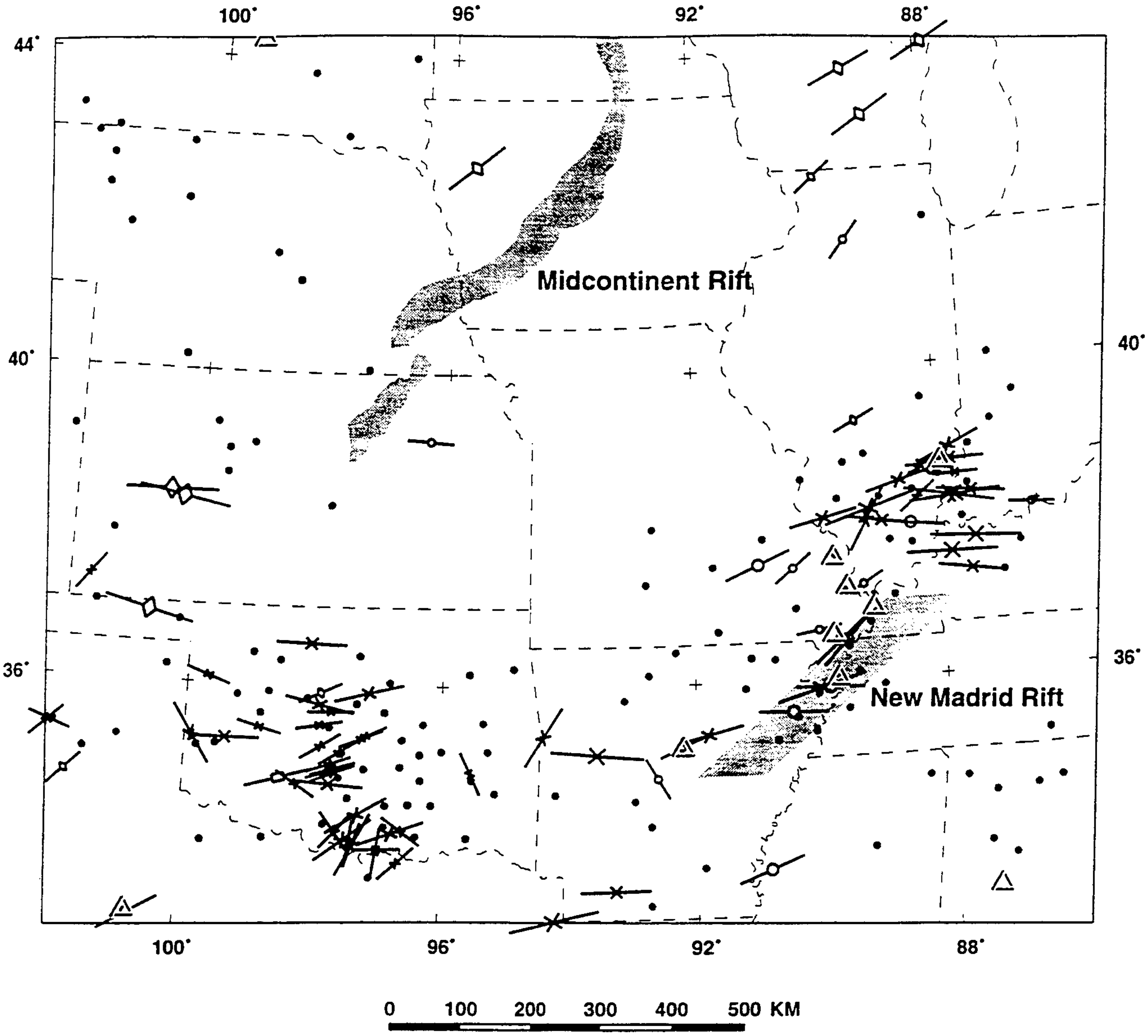

Figure 67. Seismicity and maximum horizontal stress directions in the central United States. The Midcontinent rift and New Madrid rift boundaries shown by shading. Magnitude 3.0 < M < 4.5 epicenters are shown by circles; 4.5 < M < 6.0 epicenters are indicated by open triangles. Line lengths of stress data are proportional to quality and center symbol indicates data type. From Zoback and Richardson, 1996.

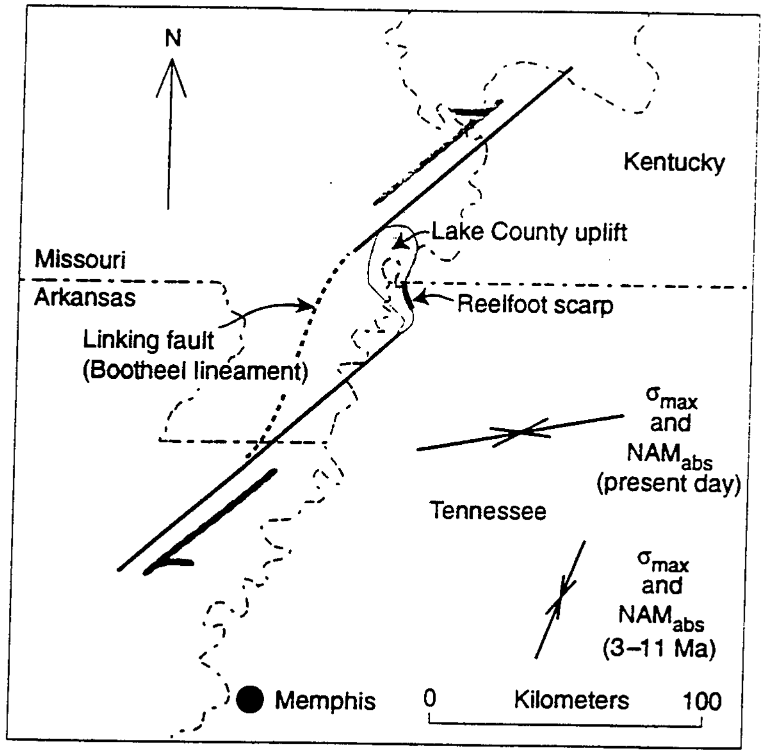

Figure 68. Schematic view of faults inferred from seismicity and surface features in New Madrid seismic zone. The right-lateral sense of displacement across the main faults is supported by the existence of a region of active uplift in the left step-over (Lake County uplift), which currently has a structural relief of 10 m above the local floodplain. The southeastern edge of Lake County uplift is also marked by an active fault (Reelfoot scarp) that may also be the surface expression of a thrust fault inferred from recent microseismic studies. Arrows show plate motions (NAM_{abs}) and presumed maximum horizontal stress directions at New Madrid for the periods 0 to 3 Ma and 3 to 11 Ma. From Schweig and Ellis, 1994.

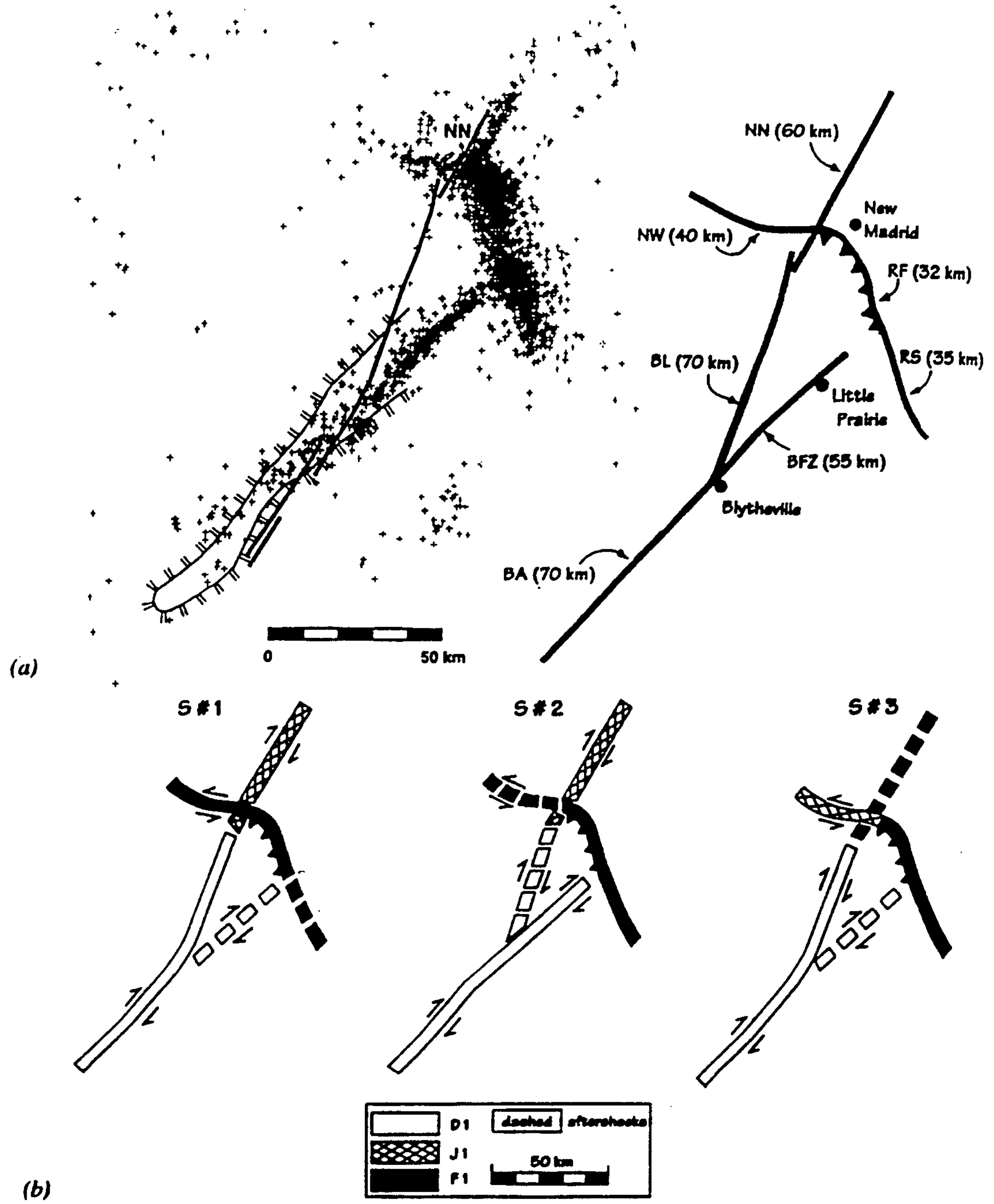

Figure 69. (a) Fault segmentation of the NMSZ. Seismicity of the NMSZ, the Blytheville arch, and the Bootheel lineament/NN fault (left) yield the seven segments (right) identified as: BA, Blytheville arch; BFZ, Blytheville fault zone; BL, Bootheel lineament; NW, New Madrid west; NN, New Madrid north; RF, Reelfoot fault; RS, Reelfoot south. Segments NW and RS are defined solely from seismicity. (b) Possible fault rupture scenarios (S#1, S#2, S#3) for the 1811-1812 D1, J1, and F1 earthquake sequences, using the seven fault segments of (a). Based on historical and physical constraints, the D1 principal event must rupture BA, and the F1 prinicpal event must rupture RF in all scenarios. S#1 is the favored scenario. From Johnston and Schweig, 1996.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 1998	Final report

4. TITLE AND SUBTITLE
Seismic Hazards of the Upper Mississippi River Embayment

5. FUNDING NUMBERS

6. AUTHOR(S)
Roy Van Arsdale

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Geological Sciences, University of Memphis, Memphis, TN 38152

8. PERFORMING ORGANIZATION REPORT NUMBER
Contract Report GL-98-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers, Washington, DC 20314-1000;
U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Earthquakes are a major hazard in the middle Mississippi River valley of the upper Mississippi embayment. Microseismicity along the New Madrid seismic zone is illuminating faults that are believed responsible for the great New Madrid earthquakes of 1811-1812. These faults are right-lateral strike-slip faults within the Blytheville arch and western margin of the Reelfoot rift that are linked by the southwest-dipping Reelfoot reverse fault. The Bootheel lineament and back thrusts of the Reelfoot fault may also have slipped in 1811-12. Geomorphic effects of the 1811-12 sequence include displacement of the Mississippi River; uplift of the Lake County uplift, Tiptonville dome, Blytheville arch; subsidence of Reelfoot Lake, Big Lake, and Lake St. Francis; landslides on the eastern bluffs of the Mississippi River valley; and extensive liquefaction. In addition there is evidence for 1811-12 landsliding on the eastern margin of Crowley's Ridge, formation of a lake on the Obion River, and formation of seismic craters on the loess-covered eastern Mississippi Valley bluffs.

Peripheral to the New Madrid seismic zone; the Big Creek, Commerce, and Crittenden County faults have Holocene displacement and faults along the margins of Crowley's Ridge have Pleistocene displacement. The margins of Sikeston Ridge are underlain by faults that apparently lifted the ridge in Quaternary time. Similarly, the eastern Mississippi Valley

(Continued)

14. SUBJECT TERMS

Earthquakes	Paleoseismicity
Mississippi Valley	Tectonics
New Madrid	

15. NUMBER OF PAGES
132

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

13. (Concluded).

bluffs are underlain by faults that appear to have affected the current position of the Mississippi River. Thus, there is evidence for widespread Quaternary faulting within the upper Mississippi embayment.

Paleoliquefaction and trench excavations across the Reelfoot fault reveal a minimum of 3 prehistoric earthquakes and an estimated recurrence interval of 450 years. This very high strain rate may be transitory and/or deformation may move around the upper Mississippi embayment through time. Since the Plio-Pleistocene Lafayette Formation and subsequent Quaternary section is incised into the Eocene section, it appears that the northern Mississippi embayment has been rising during Quaternary time. Thus, the widespread faulting may be a consequence of Quaternary uplift of the northern Mississippi embayment.

Future earthquakes would cause widespread and potentially catastrophic effects on the built environment of the Mississippi River. Of particular concern is the Reelfoot reverse fault that trends from near Dyersburg, Tennessee, to New Madrid, Missouri. Displacement, like that which occurred on February 1, 1812 on the Reelfoot fault and its associated back thrusts, would displace the Mississippi River bed at a minimum of 5 locations resulting in breaking of river levees, warping the river profile, and forming temporary ponding and rapids/waterfalls. Liquefaction was dramatic in 1811-12 and is also a major concern in future earthquakes. Although the water table is generally lower today in the Mississippi River valley due to drainage ditches, it remains high below the river levees. The levees may be vulnerable to liquefaction effects.